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STRUCTURAL ANALYSIS AND MODELING FOR COMMAND DECISIONS DURING FIRE ON BOARD SHIPS

by

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The appropriate models of fire development were created. They were designed in a way of using only those data that were possible to observe during a fire aboard. Depending on availability and quality of current information about the fire, an informative tree of alternative scenarios of the fire hazard analysis and command decisions was developed.

Conducted in terms of decision theory concept, formalization of fire-fighting procedure permitted to accomplish structural and cost benefit analysis of the command decisions during a fire aboard. Relevant chronological decision tree diagrams were designed. Structural analysis proved that application of information technology and new method of gas pressure monitoring significantly increases efficiency of command decisions during a fire without considerable additional costs.

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STRUCTURAL ANALYSIS AND MODELING FOR COMMAND DECISIONS DURING FIRE ON BOARD SHIP.

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ABSTRACT

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A. MAIN PECULIARITIES OF A FIRE ABOARD

Fire aboard any autonomous object, such as a ship or submarine, is a very dangerous emergency which has some specific features and peculiarities. These peculiarities mostly depend on the structure of a ship's compartments and equipment (apparatuses) located within them. The main peculiarities are comparatively small free volume of compartments that are heavily overloaded by the equipment, physical separation of a ship's compartments from the earth's atmosphere, comparatively high probability of the flame ignition and a fire emerge aboard. Let's discuss these peculiarities in detail.

First, *design of a ship's compartments and their overloading by the equipment.* Compartments of a ship (especially, combat ships) are rather complicated engineering constructions heavily overloaded by equipment and ship's apparatuses. Such overloading is necessary in order to reduce excessive buoyancy of a surface ship (for reduction of its surface measurements and increase of a combat vulnerability). Overloading by an equipment is much more important for submarines whose buoyancy should be so tiny for a fast submerging and hence providing their stealth. However, an equipment overloading worsens a fire safety of ships because it complicates a fire detection and fire suppression. In fact, overloading of a ship's compartment does not permit to apply the major fire-extinguishing means that are efficient in the case of direct delivering fire-extinguishing agent to the combustion zone. Fire detection is worsened because of low visibility through a firing compartment. Overloading causes lack of ventilation within a compartment; therefore, even a small flame produces so much smoke that causes further decrease of visibility and opportunity to detect and estimate actual scale of a fire.

Second, *separation of a ship compartment gas milieu from the earth's atmosphere.* The main factors, which determine a fire dynamics and its development, are oxygen concentration and gas pressure within ship's compartment. Because the milieu of a compartment might be separated from the earth's atmosphere, oxygen concentration and gas pressure can be different from regular values. So, fire dynamics can also be different. The bigger an oxygen concentration and gas pressure within a compartment, then more intensive and powerful a fire, and vice versa. On the other hand, if a compartment is closed, the oxygen concentration decreases while a fire is going. The oxygen starvation will create a specific phenomenon called a fire self-extinguishing. Then bigger the scale of a fire and less a free volume of a compartment, then the faster an oxygen starvation occurs and shorter the timing of a fire development before its self-extinguishing.

Separation of ship's compartments from the earth's atmosphere has other negative aspects. For instance, submarines (and sometimes surface ships as well) are equipped by special technical systems, which maintain normal atmospheric conditions within compartments in the case of their absolute separation from the earth's atmosphere. Such systems produce or regenerate pure oxygen to maintain regular oxygen concentration in compartments. For this purpose, these systems might use special chemicals that are extremely dangerous because of their flammability. Though these chemicals are kept on submarines with great care, they can induce catastrophic circumstances in the case of direct flame or heat impact and truly after the touch with water. The fatal fire accident with the Soviet submarine *Komsomolets* is an example of such kind of catastrophe.

Because the level of ignition (the initiation of flaming combustion) of materials strongly depends on the oxygen concentration, the autonomy and atmospheric separation of ship's compartments increase the likelihood of a fire emerge. It sometimes takes place as a result of loosing the control of the atmospheric conditions in compartments and particularly as a result of the oxygen concentration increase more than regular meanings (in the earth's atmosphere, the mass oxygen concentration, $x=0.232$). For example, according to [Nilsen, et al., 1997], one of the possible reasons for the fire on the Soviet submarine *Komsomolets* (April, 1989) was "the concentration of oxygen in the seventh compartment [that] was too high, setting off short circuits in the electrical system,"[Nilsen, et al., 1997, p.4].

Third, *comparatively high probability of the flame ignition and a fire emerge aboard.* In addition to a possibility of the excessive oxygen concentration in compartments, a comparatively high level of probability of the flame ignition and a fire emerge is determined by the high concentration of electrical and heat production equipment within ship's compartments. High density of locating the electrical equipment with comparatively big electrical voltage and power creates considerable value of the total electrical capacity of a ship. Such a situation objectively creates conditions for high probability of electrical shorts and hence fire ignitions. Heat production equipment (first of all the elements of the ship's power plant that are usually located so tightly), also increases a probability of fire ignition because of the total high temperature surface of this equipment.

Some of the ship's technical systems might be potentially dangerous with respect to a fire ignition and its development. For instance, air pressure systems of submarines that are necessary not only for merging /submerging the vessel, but also for supporting the functions of the ship's equipment and maintaining normal atmospheric conditions aboard, are dangerous because these systems are potential oxygen suppliers for the fire in the case of their damage. According to the analysis of the fire accident with the Soviet submarine *Komsomolets* [Nilsen, et al., 1997], the main reason of catastrophic circumstances of the fire was the damage of the high-pressure air system of the submarine and uncontrollable supply of the fresh air into the accidental burning compartment. Such a situation created the fatal conditions for two reasons. First, the accidental compartment was considerably pressurized by the high-pressure air system. It significantly amplified the scale and intensity of the combustion process and did not allowed to implement efficiently the system of fire suppression. Secondly, a permanent supply of the fresh air maintained perfect conditions for the keeping the fire development that finally destroyed the pressure hull of the submarine and caused it to sunk.

Finally, *the high probability of a fire emerge on a ship* is determined by the presence of own different types of weapons aboard and possibility to be attacked by an enemy weapons.

All of the above shows that a fire on a ship has happened as a result of the objectives that can not be eliminated; therefore, fire occurred in the past, they have been taken place now, and they definitely will happen in the future.

B. VARIATIONS OF PRINCIPAL PARAMETERS OF A COMPARTMENT MILIEU WITH TIME AND THEIR IMPACT ON PEOPLE AND EQUIPMENT DURING A FILE ABOARD

Despite of the fact that each fire is a rather complicated physical phenomenon that depends on tremendous number of different random and nonrandom factors, it is possible to subscribe its principal parameters and their impact on people and equipment. The principal parameters of the fire that might influence on people and equipment of ship are fire fume, high temperature, oxygen concentration, and concentrations of gases produced as a result a combustion chemical reaction (such as carbon dioxide, CO_2, carbon monoxide, CO, and others). As an example, Figure 1 represents variations of principal parameters of milieu with time during a free fire development within a closed compartment of ship. (Free fire development means that none fire suppression means are implemented; therefore, the fire develops free until self-extinguishing because of oxygen starvation). According to Drysdale (1992) and Astapenko et al. (1988), an entire fire process may be divided into three periods: (1) a period of fire expansion, (2) a period of quasi-stability, and (3) a period of extinguishing.

An expansion period of fire development can be going on from few seconds to several hours. It depends on concrete physical conditions of milieu and type of burning materials. Sometimes, this period in its turn might be divided into *ignition phase* (which starts from heating and thermal decomposition and ends an ignition of fuel (a flame appearance) and *a fire expansion phase* itself (when a flame begins to spread out involving more and more burning materials into a combustion process). An ignition phase is usually happens without considerable change of temperature and gas concentrations of a compartment milieu, but it can produce fumes, which might be an objective signal of the beginning of the fire. A fire expansion phase is much more vigor and fast than an ignition phase. It is followed by fast and considerable growth of the scale and temperature of fire, and significant change of the gas concentrations in a compartment (see Fig.1). Nevertheless, this phase of a fire can be also sluggish because of the type of burning materials and the speed of oxygen supply into the combustion zone.

A quasi-stability period occurs when the scale of the fire (a fuel surface area, A_f) and the parameters of the compartment milieu begin to stagnate (see Fig.1) though further slow temperature growth in a compartment might continue. In contrast, oxygen, carbon di- and mono oxide concentrations keep varying with almost the same speed as they did during an expansion period. Temperature and fire stabilization (or quasi-stabilization) happens, on the one hand, as a result of oxygen or fuel supply shortages in an accidental compartment, on the other hand, as a result of quasi-equilibrium between fire heat energy release into compartment and heat energy loss from the burning compartment. During that period, an average gas temperature in a compartment can raise up to 200-300C and more, as long as local temperatures might be 400-800C. Total duration of a quasi-stability period is from several minutes to several hours.

An extinguishing period is a final period of a fire. It characterizes by the total slowdown of all physic and chemical processes and temperature decrease in a compartment as well. Lack of the oxygen or fuels causes self-extinguishing of flame; nevertheless, a process of decomposition might take place for a long time. For closed compartments of ships (it means there is no gas exchange between the burning compartment and surroundings), self-extinguishing usually occurs as a result of oxygen starvation (when x=0.12-0.13). Therefore, it is dangerous to open the damaged compartment after fire extinguishing because the fresh air coming from nearby compartments can induce backdraft.

If active means of fire suppression are used, the character of the fire development and variations of principal parameters of the compartment milieu with time might be completely different from the free fire development. For instance, in Fig. 1, the dotted line shows possible variation of gas temperature with time, if the fire suppression means was successfully used at the moment t_s. From Fig.1, can be seen that the sooner a fire suppression means are used, the faster and more efficiently the fire will be extinguished.

C. PRINCIPAL WAYS OF FIRE SAFETY AND FIRE PROTECTION ABOARD

All principal ways of fire safety and fire protection aboard might be divided into two groups: constructive and organizational. The purpose of constructive ways is to provide fire safety and fire protection of a ship by means of specific ship's design solutions and technical fire detection/suppression systems. Organizational ways are those which based on specific actions of a ship's crew to prevent initiation a fire, and, if a fire occurs, these actions are conducted to prevent the propagation and suppress the fire.

1. Constructive ways

They can be also divided into two main groups. *Passive constructive ways* is the first group that includes next technical and ship's design solutions:

- dividing a ship's hull into water-and gas-tight compartments. Such a design solution means that an entire hull of a ship (submarine) can be quickly separated onto several water- and gas-tight compartments by means of special doors and hatches (see, for example, Figure 2). From the point of view of fire protection, this measure helps to prevent smoke (fume) propagation and suppress the fire because of oxygen starvation in a damaged compartment.

- technical systems of fire detection. A fire detection system is a device that gives a warning when fire occurs in the area protected by the device. It includes one or more detectors, relays the alarm to those endangered by the fire or those responsible for fire-fighting operations. The detection system can also activate fire-extinguishing equipment. The types of fire detection systems approved for use aboard ship include the following [O'Neill et al., 1975]:
    - Automatic fire detection systems
    - Manual fire alarm systems
    - Smoke detection systems
    - Watchmen's supervisory system
    - Combinations of the above

Active constructive ways of fire safety and fire protection include such technical devices and systems that are directly used for fire suppression or prevention of the fire propagation. All these devices and systems can be distinguished by the type of extinguishing agent or by the size of a device (system) and its extinguishing power. Eight extinguishing agents are in common use. Each is applied to the fire as a liquid, gas or solid, depending on its extinguishing action and physical properties. Because an efficient use of each agent depends on the *class of fire*, we shall briefly discuss these classes. For fire-fighting purposes, there are fife fire classes [O'Neill et al., 1975; Gates, 1987]:

- Class A fires (common flammable solid fuel)
- Class B fires (flammable liquid or gaseous fuel)
- Class C fires (electrical equipment)

- Class D fires (combustible-metal fuel)
- Class F fires (fuels that do not need an external oxidation material for a combustion process: missile's fuel, gunpowder, chemicals for atmospheric regeneration, etc.)

The most popular extinguishing agents are [O'Neill et al., 1975; Gates, 1987]:

- *Liquids:* water spray; foam.
- *Gases:* carbon dioxide (CO2); halons (1211 or 1301).
- *Solids (Dry Chemicals):* monoammonium phosphate; bicarbonate; potassium bicarbonate; potassium chloride.

On Figure 3, the actions of extinguishing agents on the different classes of fire are shown [O'Neill et al., 1975].

Depending on the size and extinguishing power all fire extinguishers can be divided on:

- Portable and Semi-portable devices (extinguishers).
- Fixed Fire-Extinguishing Systems.

Portable extinguishers can be carried to the fire area for a fast attack. However, they contain a limited supply of extinguishing agent. In most cases, continuous application can be sustained for only a minute or less. In fact, they are efficient for the nascent fires with tiny scale and small fire surface area (A_f<1 m^2). When the fire is big or powerful, fixed fire-extinguishing systems should be used. United States ships use seven major types of fixed fire-extinguishing systems [O'Neill et al., 1975; Gates, 1987]:

- Fire-main systems
- Automatic and manual sprinkler systems
- Spray systems

- Foam systems
- Carbon dioxide systems
- Halon 1301/1211
- Dry chemical systems

The efficient extinguishing system is the halon system. Unfortunately, halons have reportedly damaged the earth atmosphere; therefore, according to the *Montreal Protocol* [Blackmore, 1994], all countries must stop using the halons. Though many countries conduct research, a satisfactory substitute of the halons has not been found yet. From the point of view the British Navy, there is currently only one other approved extinguishing gas and that is carbon dioxide (CO_2) [Blackmore, 1994]. But it has major disadvantages as between 4-5 times the storage capacity required for halon is necessary for CO_2, to provide an affective extinguishing concentration. Of even greater concern is the potential for fatalities if there are lapses in maintenance procedures or training because of the high toxicity of carbon dioxide) [Blackmore, 1994].

In order to fight major fires, US warships are provided with three basic types of fire-fighting systems. The first is a seawater fire main, which can feed hoses for dousing the fire and boundary cooling which prevents the spread of fire. The foam AFFF can be produced by using special adapters on the hoses. (AFFF cannot be used for extinguishing fires in compartments with electrical equipment.). The second is system of fixed pipework and nozzles, which can be automatically triggered to deliver extinguishing agents [Gates, 1987]. The third is a halon system, which is efficient but for only closed compartments of ships. In addition, even halon has flaws. The halon agents do not cool so they will not prevent re-ignition of a persistent source of heat. Secondly, it is toxic;

therefore, its implementing requires additional caution and control.

2. Organizational measures

Organizational measures of *fire safety* aboard include specific actions of a ship's crew to prevent initiation a fire. Such actions might be:

- special order of keeping, using, and throwing away flammable materials;
- careful organization and specific regulations for conducting any activity which deals with an open flame (welding works, smoking of personnel, etc.);
- clear individual duty and responsibility of each member of a crew for maintenance of fire safety conditions in each ship's compartment and working place, for obeying fire safety order during routine business aboard, etc.

Organizational measures of *fire protection* are specific chain of command and actions of a ship's crew when a fire occurs. The main peculiarity of the chain of command when a fire occurs is extreme *simplicity and centralization*. Both elements of this organizational structure are necessary because the fire-fighting actions must be conducted fast and vigorously. Efficiency of these actions would greatly depend on quick informative feedback between commanding officer (CO) of a ship who is responsible for fire-fighting command decisions and all members of a crew who must conduct fire-fighting actions. It is obviously, that fast and vigorous actions of a crew during a fire-fighting procedure are impossible without special preliminary *training of personnel.* Such training is usually conducted at special training places that are able to create real fire environment aboard or directly on a ship as well (in the second case, only organizational aspects and elements of fire-fighting procedure are repeated). During training, personnel of a ship exercises next basic elements of fire-fighting procedure:

- extinguishing fires of different classes (usually, A, B, and C classes);
- using different types of fire means and fire-protection equipment;
- actions of special teams for inspecting a burning (or after-burning compartment).

In addition to the training of fire-fighting personnel in real fire conditions at the special training centers, a virtual reality technology has begun to use for fire-fighting training for the last few years [Tatem and Tate, 1996]. A new technology-virtual reality-can be used as a means for damage control training without costly live fires. In this application, a human operator can be immersed in a realistic but virtual environment to develop damage control skills without safety and environmental concerns [Tatem and Tate, 1996]. "Virtual environment (VE) training can bridge the gap very effectively between the classroom and the live trainer. VE can provide the opportunity in individual and team training for exposure to unlimited fires, to study the fire physics of each, and to evaluate the damage control options than can be taken."[Tatem and Tate, 1996].

Among compulsory training elements, there is a training of special team that must be ready to inspect the damaged compartment after fire termination or even accomplish a fire-fighting procedure within a burning compartment [Blackmore, 1994]. This tough rigorous procedure for sending a man-team into a damaged compartment has been existed in the British Navy [Blackmore, 1994] and in navies of other countries including Russia. This measure has been necessary to gain more information within a compartment where a fire sensor had triggered [Blackmore, 1994], or to exam damaged compartments in order to recognize the exact location of the source of a fire and its scale. Such a rigorous procedure is a signal that nowadays fire safety and fire protection systems of the warships are not absolutely effective and are not able to relinquish direct participation of manpower in the process of early estimating and extinguishing a fire.

D. RECENT EFFORTS:

1. IT Applications

Over the dates, advantages of the modern information technology (IT) have begun to be used for fire protection of ships. "Information display and distribution is necessary to pass damage control information between a number of operating positions throughout a ship and to ensure it may be displayed when and where required." [Blackmore, 1994, p.115]. According to [Blackmore, 1994], the British Navy is developing Damage Control Information Displays (DCID). These provide a full ship-wide electronic incident board and information display network. It is considered that such a system would gather information from the sensors in order not only to recognize the fact of a fire, but also to perform "rapid discrimination between compartments on fire and those, which are simply smoke logged."[Blackmore, 1994, p.115]. The authors hope that this new information system permits to abolish participating personnel in a process of inspecting the incident compartments for providing real information about the scale and extent of the fire and making command decision of the fire-fighting. However, from the [Blackmore, 1994], it is not clear how the authors of this new information system are supposed to achieve their goal, because, among possible sensors that a new system will includes, they named traditional sensors of smoke, heat, and flame detection. These sensors and systems, which use their information, can help to provide atmospheric monitoring in damaged compartments. But it will be require tremendous amount of the sensors that must be placed in each comparatively autonomous space of a compartment or even in each electrical cabinet and any other apparatus, which is potentially flammable. In addition, such a damage control information system will need corresponding complicated software in order to deal with so voluminous volume of original information. Finally, because of complexity, a DCIS would be cumbersome and expensive technical structure.

In addition to the DCIS, it is believed that greater use of closed circuit television should be useful for fire-fighting analysis and command decision process. According to [Blackmore, 1994], this TV system will enable the ship's Command to evaluate the situation first hand and prioritize their approach. However, from our point of view, potential benefits of using a TV system are doubtful because of smoke and hence low visibility within damaged compartments and high vulnerability of the elements of a TV system with respect to heat of a fire.

2. Modeling

As long as damage control information systems (DCIS) have are used, a fire preliminary analysis of sensors' information, estimating, and even predicting fire development aboard have begun to develop as well. Fire models may be divided into two basic groups: (1) probabilistic fire models (see, for example, Watts, 1991) and (2) deterministic fire models. Both of them in their turn can be subdivided into different types depending on the physical conditions and place where a fire occurs and depending on the practical goal that this type of model should achieve. However, barely any fire models have been developed for using in DCIS for estimating and prediction of an actually developing fire aboard. The main reason is that the current deterministic fire models have been developed on the assumption that the information about original parameters of fire is available. Specifically, these deterministic models have taken as given such original parameters of fire as fire flame (pool) area, location of the source of flame in a compartment, the types of currently burning materials, etc. Current models can be used for DCIS, if we know the original parameters of a fire that, in our case, are barely might be estimated by the standard means (for example, by using fire detection sensors or by personnel report). Thus, current models should be modified in a way to use only that objective information which can be actually received from the damaged compartment. Or, we have to find new sources and methods of deriving an objective current data of a fire development.

E. PROBLEMS OF COMMAND DECISION PROCESS DURING A FIRE ABOARD

A commanding officer (CO) who must directly manage a fire-fighting process often has difficulties with respect to objective analysis of a current situation on a ship and, particularly, in damaged compartments. Oral reports of the crew members, on the one hand, and current data from many a ship's information systems (including DCIS), on the other, can create a contradictory picture that a CO cannot digest correctly in order to make command decisions. Moreover, despite the volume of current information that overloads a CO and his staff, the most important data about the fire development (scale, exact location, timing) and efficiency of conducted fire suppression actions are usually absent.

The effectiveness of a command decision process during a fire aboard depends on four factors:

- Factor 1. Objective current information about the fire development, its scale, location, timing, and possible scale the ship's damages;

- Factor 2. Information about ship's apparatuses and their working capabilities;
- Factor 3. Information about actual current actions of a crew in an emergency (damaged) and undamaged compartments of ship;
- Factor 4. Personal performance experience of a commanding officer (CO) to estimate, predict a current situation aboard, and to make managerial decisions.

Factors 2 and 3 are usually implemented satisfactorily. Factor 4 is rather subjective and depends on human and psychological peculiarities of a CO; therefore, it cannot be considerably changed. So, the main problem is factor 1 because regular manners of gathering information during a fire emerge and development is an oral report of personnel (by means of telecommunication materiel) to a CO. This manner is ineffective and mostly subjective. Due to lack of timing, personnel are usually not able to report their current actions and barely able to observe any objectives of fire development and scale of damage; therefore, these reports are scarcely helpful and often distort the real situation on a ship. Though modern ships might be equipped by special technical systems of detecting a fire and monitoring atmospheric conditions (we discussed this issue before), this information is usually so great, uncoordinated, and messy that a CO and a ship's crew aren't able to use it efficiently in order to suppress a fire and make other managerial decisions.

A good example of ineffective command decision process can represent the fatal incident with the Soviet submarine *Komsomolets*. At the beginning, nobody could learn the actual scale and power of the fire though the CO had received a report from a sailor that a fire had started. The CO also received information from the special ship's monitoring system about high atmospheric temperature within an accidental compartment. Not knowing the real scale and power of the fire, the CO ordered the implementation of regular procedures of fire inspection in order to choose a proper means of fire suppression. It was a mistake that worsened the situation. Valuable time was wasted, the fire was not suppressed, and finally, the submarine sank. The majority of the crew died either during fire fighting aboard or in the cold water of the sea after the submarine catastrophe [Nilsen, et a1., 1997].

F. OBJECTIVES (REASONING FOR RESEARCH)

First, despite of significant development and use new methods and means of fire detection and suppression, fires aboard have continued to occur during peaceful time, and they will definitely happen during warfare activities. For example, according to the current statistics of the Royal Navy [Blackmore, 1994], on average 130 fires are reported each year. Similar situations have taken place in other state navies because:

- design of a ship's compartments and their overloading by the equipment;
- comparatively high probability of the flame ignition and a fire initiation aboard;
- location of weapons and other materials with high level flammability.
- low visibility within compartments as a result heavy smoking at the very beginning of a fire.

Second, separation of a ship compartment gas milieu (that is common for submarines) causes some specific feature of a fire development which complement difficulties of the fire detection, estimating, and suppression the fire: possibility of increase gas pressure and oxygen concentration within a damaged compartment, significant smoking, and difficulties of evacuation the crew from the damaged compartments.

Third, despite of considerable progress with respect to implementation of information technology (IT) for monitoring and estimating the fire and atmospheric conditions aboard, some key-parameters of the fire such as its scale, fire pool area (current surface area of the burning materials) cannot be determined by the usual fire detection sensors. Therefore, severe procedure of visual inspection of a damaged compartment by the personnel has still taken place.

Fourth, nowadays mathematical models of fire development are barely useful for implementation in damage control information systems (DCIS), because they have been developed on the assumption that all original parameters of a fire are known. But, in many cases, preliminary knowledge of these parameters is questionable. Thus, it is quite necessary to develop a model, which will use those parameters that can be currently measured or estimated during a fire aboard.

Fifth, a commanding officer (CO) has difficulties while he makes command decision during fire-fighting actions, and sometimes these decisions are not efficient and prominent. It has happened as a result of inability to estimate real scale and scenario (picture) of the fire development; therefore, a CO cannot forecast actual hazard of fire and make efficient command decisions. Because of shortage of objective information, a CO and the crew spend too much time for dangerous inspection of a damaged compartment and indirect evaluation of the fire parameters. It decreases an efficiency of a fire-fighting procedure and sometimes leads to fatal circumstances.

Sixth, the main goal of our research is to examine opportunities for the application of information technology (IT) through modeling and structural analysis for supporting command decisions during a fire within closed compartment of ship. Specifically, our research questions and tasks are:

- To examine traditional and nontraditional objective parameters of a compartment atmosphere that are available for measuring and using for fire estimation and fire modeling in closed compartment of ship.
- To investigate an opportunity of application of the gas pressure monitoring within damaged compartment for estimating a fire scale, its dynamics, and timing of a free fire termination.
- To develop and discuss possible models of fire development within closed compartment of ship, which are based on the gas pressure monitoring and observing the other available parameters of the atmosphere within damaged compartment. (To develop informative tree of monitoring and hazard analysis during a fire aboard.)
- To examine possible alternative scenarios of estimating a fire scale and command decisions for fire suppression. (Actual chronological tree of the events and command decisions during a fire aboard.)

II. THE GAS PRESSURE MONITORING ABOARD IS AS A NEW MANNER OF FIRE HAZARD ESTIMATING FOR COMMAND DECISIONS DURING A FIRE FIGHTING ABOARD

In chapter I, it was shown that monitoring regular atmospheric parameters (gas temperature, concentrations of different specific gases) throughout the space of an accidental compartment of ship is not quite efficient way to estimate such important characteristics of fire development as the fire scale, fire pool area, and timing of self-extinction of fire within closed compartment. The main reason is space unevenness of a temperature and gas concentrations' fields throughout a compartment that requires considerable amounts of temperature and gas concentrations' sensors and complicated technique of the data interpretation. Therefore, in this chapter, a new indirect method of estimating a fire pool area, scale, and timing of fire development in a closed compartment will be discussed. Developed in Reference [Nikitin, 1998a], this new method is based on measuring and monitoring average gas pressure in an accidental compartment that is much more efficient and productive with respect not only necessary amounts of gas pressure sensors, but an opportunity of estimating and predicting a fire development and fire termination as well.

A. ESTIMATING AND PREDICTING A FIRE POOL AREA BY MONITORING GAS PRESSURE IN A CLOSED COMPARTMENT OF A SHIP

Fire pool area is one of the most important features of a fire in closed compartments of ships. Estimation of the fire area is important because it permits to choose effective method of extinguishing fire or to apply mathematical fire modeling which is usually based on knowledge of the fire pool area as one of the original parameters. However, such estimation when an actual fire occurs is a difficult task. For example, if a fire occurs on a ship (submarine) those compartments are heavily occupied by equipment, it's very difficult or even impossible to determine the flame (fire pool) area and, consequently, to estimate the actual scale and potential danger of the fire for the ship and its crew. On the other hand, estimating the fire pool area (and other parameters of a fire as well) by measuring the temperature (or gas concentrations') fields is rather complicated and barely reasonable task because these unsteady fields are so irregular and uneven through the space of a fire closed compartment. So the measuring these fields requires a lot of temperature and gas concentration sensors that should be installed throughout the entire compartment. At the same time, it is well known that a gas pressure and its variations during a fire development are much more regular throughout the space of a closed compartment. So, measuring the gas pressure and applying these data for estimating and predicting a fire development within a closed compartment looks much attractive.

Nikitin (1998a) proposed an indirect method of estimating the fire pool area was proposed. This method is based on correlation between the fire pool area and the rate of gas pressure increase within a closed compartment during the first period of the fire development.

B. PRELIMINARY EXPERIMENT AND RELEVANT THEORY OF FIRE POOL ESTIMAING BY THE GAS PRESSURE MONITORING

Analysis of experimental data shows some correlation between the fire pool area and variation of gas pressure within a closed compartment. For instance, during experiments with the fires conducted by the author of this paper, it was noticed that, at the beginning a fire development (while the average temperature (gas pressure) in a compartment raise up), the bigger fire pool area, A_s, induces a larger rate of the air pressure increase, $\dot{p}$, in a closed fire compartment. As a result, we decided to investigate this phenomenon by means of the special full-scale tests performed in the closed steel compartment at the Naval Research Laboratory (Sevastopol, Ukraine).

In that compartment (the internal volume, V=46m^3), six distinct test series were conducted. The burning material was diesel fuel placed on the liquid (or fire) pool with constant area (A_s=0.22 m^2). Every test seria was different from others with respect to the liquid pool location in the compartment. From one test seria to another, we changed the clearance between the liquid pool and the ceiling, l, and the distances between the liquid pool and the walls of the compartment. We also changed the amount of equipment placed in the compartment to alter the total area of the heat-transfer surface between the fire and the walls (constructions) of the compartment.

The most interesting results of these experiments are represented on Figure 4. From this figure, we may see that variation of the average air (gas) pressure of the compartment with time during fire development significantly depends on the location of the fire pool and the amount of the equipment (the surface area of the compartment). At the same time, during the first period of the fire development (in our experiments, it was 50-60 s), maximum rate of the air pressure increase, $\dot{p}_m$, for every test seria is approximately the same. (See also, Table 1, columns 1-6). The most interesting example is comparison the first test seria (when the fire pool was placed on the central point of the floor and l=1.35m) and the fourth test seria (the liquid pool was in the steel tube so that the flame of the fire didn't radiate to the compartment walls and ceiling). For these two series, though entire behaviors of the air pressure variations with time are very distinct (see Fig. 4), and the biggest air pressures are significantly different (p=8*10^5 Pa and 16*10^{5}Pa, accordingly), the maximum rates of air pressure increase are approximately equal ($\dot{p}_m$=156 Pa/s and 177 Pa/s). This phenomenon and such comparable maximum rate of the air pressure increase might be explained in terms of heat transfer between the fire flame and the constructions' surface of the compartment.

To explain this phenomenon, we suggested that during the first period of the fire development, heat transfer happens mostly by means of the heat radiation from the fire flame to the constructions' (or equipment's) surface of the compartment. At the same time, the portion of the heat transfer by convection is insignificant. Let's see this idea in details. For the closed compartments (that means there is no gas exchange between the firing compartment and surrounding area), the basic equation of energy balance is [Astapenko et al., 1988]:

$$V\frac{d}{d\tau}\left(\frac{p}{k-1}\right) = \dot{m}\eta H + h_g\dot{m} - Q_w \tag{2.1}$$

It was shown in the paper [Astapenko at al., 1988] that ratio of specific heats, k, has very small variations with time during the fire. In addition, enthalpy of the fuel vapor, h_g, can be neglected. Therefore, equation (1) might be represented as:

$$\dot{p}\left(\frac{V}{k-1}\right) = \dot{m}_s A_s K\eta H - Q_w, \tag{2.2}$$

where $\dot{m}_s$ is mass combustion rate per unit of the fire pool area, and K is combustion efficiency coefficient which depends on the ratio between actual surface area of the burning fuel and the flame projection area on a floor of a compartment, A_s. (For example, for liquid fuels, both areas are the same; therefore, K=1).

In this equation, total heat, Q_w, transferred from the fire to the constructions of compartment (walls, ceiling, floor, equipment, etc.) usually consists of two main parts: radiation from the fire flame, Q_f, and convection from the heated air (gases) to the walls, Q_c. As we noticed before, during the first period of the fire development, we may neglect the convection portion of heat transfer, Q_c. Otherwise, we would have suggested that Q_c and its variations with time during the fire did not depend on the location of the fire pool and did not depend on the value of the heat-transfer area between the hot gas layer and the surface of a compartment (constructions) that is obviously incorrect. Consequently,

$$Q_w \approx Q_f \tag{2.3}$$

For fires in closed compartments, heat transferred to the constructions by means of flame radiation might be determined [Romanenko at al., 1987]:

$$Q_f = c_0 \varepsilon \, [(T_f/100)^4 - (T_w/100)^4] A_f F_{f\text{-}w} \tag{2.4}$$

where ε --mutual emissivity determined as:

$$\varepsilon = 1/(1/\varepsilon_f + 1/\varepsilon_w - 1) \tag{2.5}$$

The shape factor $F_{f\text{-}w}$ is defined as the fraction of total radiant energy that leaves the flame surface and arrives directly on the constructions' surface. For the closed compartments, it's possible to suggest that entire radiant energy of the flame arrives on the constructions' surface; therefore,

$$F_{f\text{-}w} \approx 1 \tag{2.6}$$

During the first period of fire development:

$$T_f > T_w$$

Consequently

$$(T_f/100)^4 >> (T_w/100)^4 \quad (2.7)$$

and

$$Q_w = Q_f = c_o\,\varepsilon\,A_f(T_f/100)^4 \quad (2.8)$$

Analysis of research papers, written by different authors, shows some strong correlation between the fire pool area, A_s, and the height of the fire flame, h_f. According to [Romanenko at al., 1987], the flame height might be roughly estimated as:

$$h_f \approx 1.3D \quad (2.9)$$

Therefore,

$$A_f = 2.79A_s \quad (2.10)$$

Finally, equation (2.8) will be:

$$Q_w = 16.1\,\varepsilon\,A_s(T_f/100)^4 \quad (2.11)$$

If we insert equation (2.11) to (2.2), the maximum rate of the gas pressure increase during fire will be:

$$\dot{p}_m = \frac{k-1}{V}[\dot{m}_s K\eta H - 16.1\varepsilon(T_f/100)^4]A_s \quad (2.12)$$

During the first period of the fire development, it is possible to suggest that the values of $\dot{m}_s, \eta$, H, K, T_f, ε are varied insignificantly. In other words, we may suppose that:

$$\dot{p}_m = A_s/CV \quad (2.13)$$

or

$$A_s = CV\dot{p}_m \quad (2.14)$$

where C--coefficient which is constant in time and which might be calculated for any type of fuel (for example, by means of combustion manual):

$$C=1/[\dot{m}_s K\eta H-16.1\varepsilon(T_f/100)^4] \tag{2.15}$$

Thus, equation (2.14) shows that for any type of the burning material, the fire area is directly proportional to the maximum rate of the gas pressure increase and the volume of the compartment.

Accuracy of the equations (2.14) and (2.15) was confirmed by different experimental data conducted in the closed steel compartments with the volumes V=13.5, 32, 46, and 164m^2 respectively. The burning material was diesel fuel placed on the fire pool (which area, A_s, was kept constant in each test, but changed in different seria tests from 0.12m^2 to 1.8m^2). These experimental data are represented on Table 1 and Figure 5. For example, Figure 5 demonstrates the linear character of correlation between $\dot{p}_m$ and A_s/V. On this figure the straight line 1 was drawn by the formula

$$A_s/V=2.27\times 10^{-5}\,\dot{p}_m, \tag{2.16}$$

that was calculated for the diesel fuel by equation (2.14) and (2.15).

C. ESTIMATING THE FIRE POOL AREA IN THE CASE OF SEVERAL BURNING MATERIALS

During an actual fire, many different materials capable to combust might be located in a fire compartment. Therefore, it might be impossible to recognize what exact fuels (materials) are burning in some particular period of time during a fire development. Such a situation is very typical for compartments of ships (submarines) where assemblies of potentially combustible materials and constructions are located in a very small space of the compartment. Consequently, it is important to create some method that would be able to estimate the fire pool area and the scale of the fire when we don't have precise information about materials that are currently burning in a fire compartment. In order to do that, we may use previous results and equations (2.14) and (2.15).

First, we may prematurely analyze all materials (constructions, equipment, etc.) located in the closed compartment and, using formulas (2.14), (2.15), to determine two of them which have the largest, $\dot{p}_{ml}$ and the smallest, $\dot{p}_{ms}$ meanings of the maximal rate of the gas pressure increase at the same fire surface area, A_s. Then, for these two materials, we may draw graphs (straight lines) which reflect the values of $\dot{p}_m$ versus the values of fire pool area, A_s, by means of formulas (2.14), (2.15). These two straight lines will form a sector where the straight lines, $\dot{p}_{mi} = f(A_i)$, of all other burning materials will be located. In other words, every value of the fire surface area, A_{si}, will consistent with the range of the values of maximum rates of the air pressure increase, $\dot{p}_{mi}$, of all burning materials, and contra versa. For example, Figure 6 represents variation of A_s with the ratio $\dot{p}_m/V$ in the case when the marginal materials are diesel fuel (line 2) and wood (line 1). The majority of other ordinary carbon fuels (materials) would be located between these two marginal straight lines. From this figure, we can also see the larger fire pool area provides the wider range of $\dot{p}_m$ and the larger error of our estimation. However, at the same time, the larger fire area, the smaller probability that only one type of material is currently burning; therefore, the "actual gap" between $\dot{p}_{ml}$ and $\dot{p}_{ms}$ might be much less than the original gap that had been prematurely calculated for this particular compartment. Thus, uncertainty and the gap of the estimating the current fire pool area (A_{sl}--A_{ss}) by means of measuring $\dot{p}_m$ might be considerably reduced. For example, in some extent, it is possible to assume that the bigger fire pool area, the closer the "actual" straight line $\dot{p}_m = f(A_s)$ to the bias within the sector $\dot{p}_{ml} - \dot{p}_{ms}$, (or A_{sl}-A_{ss}).

D. ESTIMATING A FIRE POOL AREA IN THE CASE OF SEVERAL CONNECTED COMPARTMENTS

In practice, at the beginning of fire development and its detection, an accidental compartment might be unclosed; therefore, the rate of air pressure increase would be not consistent with our premature estimation by equations (2.14) and (2.15). Some portion gases will likely be transported from the accidental compartment to other, nearby compartments. For instance, such a situation is common for a submarine, the pressure hull of that is divided into several compartments by the gas-and watertight walls. Thus, each compartment can be sealed and separated from the others, in the event of a fire. However, the procedure of enclosure requires some period of time.

Let's see an example when accidental compartment has connections with two others. All three compartments are secluded from surroundings and might be completely sealed (separated) one from another for some short period of time. In this case, instead of equation (2.2), the basic equation of energy balance might be represented:

$$V/(k-1)\,\dot{p} = \dot{m}_s\, A_s K \eta H - Q_w - \dot{m}_{g1}\, c_p T_\infty - \dot{m}_{g2}\, c_p T_\infty \qquad (2.17)$$

It's possible to suggest that, at the very beginning of fire detection and sealing the accidental compartment, the average temperatures of air within all compartments are approximately even. It is also possible to assume that the energy losses of air (gases) flowing through openings between compartments are not significant; therefore,

$$V_1(k-1)\dot{p}_1 = \dot{m}_{g1}\, c_p T_\infty \tag{2.18}$$

$$V_2(k-1)\dot{p}_2 = \dot{m}_{g2}\, c_p T_\infty \tag{2.19}$$

If equations (2.18) and (2.19) insert to (2.17), then

$$(V\dot{p}+V_1\dot{p}_1+V_2\dot{p}_2)/(k-1)=\dot{m}_s\, A_s K\eta H - Q_w \tag{2.20}$$

and

$$A_s = C(V\dot{p}+V_1\dot{p}_1+V_2\dot{p}_2) \tag{2.21}$$

Following our previous reasoning and discussion, it's obvious that the fire pool area is directly proportional to the maximum value of the sum $(\dot{p}V+\dot{p}V_1+\dot{p}_2V_2)_{\max}$; consequently:

$$A_s = C(\dot{p}V+\dot{p}V_1+\dot{p}_2V_2)_{\max} \tag{2.22}$$

The case of three compartments can be generalized to the case of *n* nearby compartments; therefore,

$$A_s = C(\dot{p}V+\dot{p}_1V_1+\dot{p}_2V_2+\ldots+\dot{p}_nV_n)_{\max} \tag{2.23}$$

E. FIRE SCALE IS MORE UNIVERSAL AND RELEVANT FOR ESTIMATION OF THE FIRE HAZARD

Previous experience shows that hazard evaluation of a fire by means of estimating its fire pool area is not quite reasonable and objective because such a parameter does not depend on the volume of the accidental compartment. Two fires that have the same fire pool areas will have completely different damage and hazard effects on a ship if, for example, the free volumes of these compartments equal correspondingly $1000 m^3$ and $50 m^3$.

From our point of view, there is more efficient measure of a fire hazard effect such as the *scale of the fire within a closed compartment, Sc,* that might be determined as the ratio between heat released by the fire per unit time and the volume of the accidental compartment. In other words, the fire scale is the heat power of a fire per volume unite of a compartment (W/m^3). The most remarkable, that dimensionalities of *Sc* and $\dot{p}$ are equivalent. Certainly, the dimensionality of *Sc* is (W/m^3) while the dimensionality of gas pressure rate is (Pa/s). But after corresponding manipulations with basic dimensions that compose each of these parameters, it possible to show that they are absolutely identical. Consequently, the fire scale, *Sc,* as the most objective parameter of the fire hazard within might be directly determined by measuring and monitoring the rate of the gas pressure within an accidental compartment, $\dot{p}$, during a fire development. The fire scale, *Sc,* is more universal measure then, for example, fire pool area A_s because it allows to compare the values of the fire hazards that might occur in different (in terms of the volume) ship's compartments.

F. CONCLUSION

First, a new indirect method of estimation of a fire surface area by measuring rate of air pressure variation was created. This method is based on the notion that, for each burning material, there is correlation between the maximum rate of the air pressure increase in a closed compartment and the fire pool area. Moreover, our experimental and theoretical research stated that this correlation has a linear character. It was also shown that, at the first period of fire development in a closed compartment, the fire pool area is directly proportional to the maximum rate of air pressure increase within the compartment. Necessary formulas for calculating the fire pool area were created and confirmed by experimental data.

Second, this new method of estimating the fire surface area can be used if a compartment contains several different materials, and if it's impossible to determine what type of materials are actually burning. In this case, each value of the maximum rate of the air pressure increase $\dot{p}_m$ is consistent with the range of the values of the fire pool areas (A_{st}-A_{ss}). This range (gap) might be prematurely calculated for two marginal burning materials that have the largest and the smallest heat release capacities among all fuels located in an accidental compartment.

Third, if an accidental compartment is not completely sealed (separated) from nearby ones, it is necessary to observe the air pressure variations within each compartment and to use this information for the fire pool estimating. In this case, the fire pool area is directly proportional to the maximum sum of the products of free volumes and the rates of air pressure increase within each compartment.

Fourth, a pressure field in a closed compartment is not so irregular as the temperature or gas concentration fields are. Therefore, measuring an average pressure variation (or its rate) is much more reasonable and technically simple because it does not require too many pressure sensors in a compartment.

Fifth, a gas pressure monitoring is quite efficient, reliable, and reasonable way of estimating the fire scale for command decision during a fire aboard, particularly, for choosing the most efficient tool of fire suppression, fire modeling, and fire predicting. Therefore, application of a gas pressure monitoring in board damage control information systems (DCIS) can considerably increase their efficiency with respect the entire process of a fire fighting procedure and command decisions.

III. MODELS OF FIRE DEVELOPMENT WHICH MIGHT BE APPLIED IN DAMAGE CONTROL INFORMATION SYSTEMS

Analysis conducted in Chapter II has opened new opportunities of gathering objective information about a fire emerge, its development, and termination. The most important, monitoring the gas pressure within compartments of ship have broadened advantages of applying fire modeling for estimating and predicting principal parameters of the fire and evaluating the fire hazard. In this chapter, we will propose and discuss some concrete model of fire development in a damaged compartment and possible ways (models) of estimating the time of functioning a ship's apparatuses and equipment that is crucially important for command decisions during fire fighting and actions that help to rescue a damage ship and its crew.

A. MATHEMATICAL MODEL AND EQUATIONS FOR ESTIMATING AND PREDICTING PRINCIPAL PARAMETERS OF FIRE DEVELOPMENT WITHIN CLOSED COMPARTMENT OF SHIP

Even the most simple and approximate models of fire development assume that we preliminary know some basic original features of the burning materials and geometry of the damaged compartment. Among them are: type of burning materials (their initial combustion characteristics, $\dot{m}_s$ and H), a fire pool area A_s, and the volume of the compartment V. Such a minimum of information permits to design a model which is able to estimate and predict average parameters of the temperature, gas concentration fields during a fire. Such a sort of model for a sealed ship's compartment was developed by the author [Nikitin, 1989]. This model was developed by means of modification of the forth fundamental equations (energy, material, oxygen balances equations and the Clapeyron equation) [Astapenko,et al., 1988] for the atmosphere of the sealed firing compartment and mathematical solution these four equations as a system [Nikitin, 1989]. As a result, the equations that describe relations between average temperature, T, oxygen concentration, x, the gas density ρ and the time of a fire development were received. Particularly, these relations might be:

$$\rho / \rho_0 = (1+\theta)/(x/x_0+\theta) \tag{3.1}$$

$$\tau/\tau_0 = (1+\theta)(1-\omega)/[(\theta+\omega)^2]\ln\{(1-\omega)(x/x_0+\theta)/[(x/x_0-\omega)(1+\theta)]\} - \\ -(1-\omega)(1-x/x_0)/[(\theta+\omega)(x/x_0-\theta) \tag{3.2}$$

$$T/T_0 = 1+(M-1)(x/x_0-\omega)/[A(1-\lambda)(1-\omega)]\times \\ \times\{1-[(x/x_0-\omega)(1+\theta)/(1-\omega)/(x/x_0+\theta)]^{1/\lambda-1}\} \tag{3.3}$$

Where

$$\lambda = (\theta+\omega)/[A(1-\omega)] \tag{3.4}$$

$$\omega = c_{pg} r(T_S - T_0)/(x_0 H) \tag{3.5}$$

$$\theta = \eta r / x_0 \tag{3.6}$$

$$A = \alpha F(k-1)/(\dot{m}_S RA_f) \tag{3.7}$$

$$M = (k-1)[\eta H \dot{m}_S - 15{,}0(T_f/100)^4]/(\dot{m}_{S0} T_0 R) \tag{3.8}$$

When the gas exchange between a damaged compartment and surroundings is absent and there is none additional oxygen supply within the compartment, the change of the gas density ρ during all period of the fire development is insignificant. Consequently,

$$\rho / \rho_0 \approx 1 \tag{3.9}$$

And the equations (3.1)-(3.3) might be simplified:

$$x / x_0 = \exp\{-\theta^2 (\tau / \tau_0) / (1+\theta)\} \tag{3.10}$$

$$T / T_0 = 1 + M / [A(1-\theta / A)]\{\exp[-\theta^2 (\tau / \tau_0) / (1+\theta)] -$$

$$- \exp[-\theta A (\tau / \tau_0) / (1+\theta) \tag{3.11}$$

Equations (3.10) and (3.11) might be applied for approximate estimating oxygen concentration and temperature variations during the time of a fire development in a closed compartment.

B. MODEL OF FIRE DEVELOPMENT FOR ESTIMATING TEMPERATURE WITHIN SPECIFIC ZONES OF A COMPARTMENT

Because of possible considerable inequality of temperature and oxygen concentration fields through the space of a damaged compartment, the estimation and prediction of the average parameters of a fire development might be not enough for objective identification of the fire hazard and efficiency of the command decisions. Therefore, it is necessary to develop some methods that are able to evaluate the temperature distribution within space (or at least some specific zones) of the damaged compartment. There are many types of models that are permit to estimate the temperatures in particular zones [for example, Quintiere, 1995], but their practical application and accuracy depend on an opportunity to receive specific initial and current information not only about a fire pool area, types of the burning materials, but precise place and configuration of the surface of burning materials.

One of possible way of estimating temperature in some particular zones or points might be next. In some extent, entire temperature field within a compartment might be divided onto two zones (see Figure 7):

- zone of thermal impact of the fire
- zone of comparative safety.

At the first approach, it is reasonable assume that the volume of thermal zone, V_t, equals a current volume of atmosphere of a compartment which has already passed through the combustion zone (a zone above a surface of the burning materials where physical mixture between vaporized fuel and atmospheric oxygen and chemical combustion reaction occur). In this case, it is possible to show that a current volume V_t (a thermal zone) depends on the ratio between a current and initial oxygen average concentrations within a compartment [Nikitin, 1989]. This correlation might be described [Nikitin, 1989] by the next quite simple equation:

$$V_T / V = 1 - x / x_0 \tag{3.12}$$

If we also assume that a current energy of the fire absorbed by the compartment atmosphere has been actually distributed within the thermal zone volume, V_t, then we may write:

$$V(T - T_0) = V_T (T_T - T_0) \tag{3.13}$$

where T_T is temperature within a thermal impact zone. In other words, the temperature of the thermal impact zone can be estimating by a formula [Nikitin, 1989]:

$$T_T = T_0 + T(V_T / V) \tag{3.14}$$

or

$$T_T = T_0 + T(1 - x / x_0) \tag{3.15}$$

Thus, if we are able to estimate the average temperature variation T, we can calculate not only the current volume, but also the temperature passage within a zone of thermal impact [for example, by inserting equation (3.11) to equation (3.15)].

C. MODELS FOR ESTIMATING AND PREDICTING THE TIMING OF FUNCTIONING A SHIP'S APPARATUSES AND EQUIPMENT

Suppose that we can estimate and predict a temperature schedule within a closed compartment during a fire. Now let's discuss possible and reasonable model (or method) estimating and predicting the timing the ship's apparatuses' functioning when a fire occurs. Such an estimating for each important ship's equipment located in a damaged compartment can be provided based on a notion that functioning any equipment unit (electronic cabinet, machine, or power plant apparatus) depends on a dynamic rate of a temperature increase within this unit and gain of a critical temperature which can destroy or malfunction their functional elements. Thus, a task of estimating the timing an equipment unit functioning is divided onto several steps (or tasks):

First, preliminary, we have to determine what element of the equipment unit is the most vulnerable with respect to a high temperature impact.

Second, we need to identify the meaning of a temperature that causes the element malfunctioning (damage), T_{cr}.

Third, for each important type of a ship's equipment, we have to develop an unsteady heat-transfer model and formulas that would be able to calculate a temperature regime of the most vulnerable elements.

Finally, using a fire development model together with the unsteady heat-transfer models of the equipment, we may estimate and predict the timing, τ_{cr}, the equipment functioning at some concrete moment of a fire development. For each examined equipment unit, this timing will happen when a current temperature of a vulnerable element becomes equal the critical temperature, T_{cr} (see Figure 8).

D INFORMATIVE TREE: ALTERNATIVE SCENARIOS OF MONITORING, ESTIMATING, AND PREDICTING THE HAZARD OF FIRE DEVELOPMENT AND THEIR APPLICATION IN DCIS

Each fire is unique with respect its duplication even at the same original conditions and parameters. In other words, if two fires occur within the same compartment and place, and all initial physical conditions and objectives are the same, the actual development of each fire, in some extent, would be different. Such unpredictability of a fire development, on the one hand, and distinctive potential opportunities for taking objective current information about its principal parameters, on the other, require specific methods of the fire estimating and predicting. One of the possible ways to solve the problem of uncertainty and unpredictability of a fire propagation throughout ship's compartments is the design of *an informative tree of possible ways of fire monitoring and hazard analysis.* Such a tree will provide estimating and predicting the fire hazard depending on, first, the events that really occur during a fire, and second, an accuracy and amounts of the initial and current objective information about a fire development.

Our previous analysis showed, that there are few possible groups of objective information about a fire in a compartment that might contribute for applying specific fire models and, consequently, might provide specific abilities to estimate and predict a fire development and to determine particular ways of fire fighting and rescuing of ship. Among them:

- Location of a source of a fire within a compartment (an exact cite where a flame takes place);
- Specific type of burning materials (the knowledge of specific type apparently assumes the knowledge of combustion properties of fuels);
- The gas pressure monitoring within an accidental and nearby compartments;
- Smoke, gas temperature, and gas concentrations' monitoring.

As we showed in Chapter I, the first two groups of information can be received by directive inspection of a burning compartment by personnel. Therefore, objectiveness and probability to receive this information is comparatively low. Though, the second and the third groups of information are more reliable, and the probability to receive it is higher, we can not except the case when this information would not be taken into account. In other words, in our scenarios (tree of possible scenarios), we have to examine all possible ways and combinations of all groups of objective information.

Taking into consideration all the above, we have created the tree of possible scenarios of fire hazard analysis and appropriate specific decisions for fire suppression (see Figure 9). As we see from Fig.9, there are more than six possible scenarios of a fire hazard analysis (the scenarios that are available in the case of receiving the six group of information are drafted only approximately). Let's discuss the opportunities of each possible scenario in detail.

1. Scenario 1.

No objective information about the fire is available. In this case, no appropriate models of fire development can be used. Therefore, our opportunities to analyze possible development of the fire and probable damage of the ship and equipment are scanty. Nevertheless, we have a chance to assess possible hazard and damage if we assume that the fire is the worst among any possible. For instance, we may assume that all space of the accidental compartment is burning, and the temperature in every particular point of the space equals the flame temperature ($T_f \approx 1300K$). We also may assume that the timing of this fire is infinite ($\tau_* = \infty$). Using this intently excessive numbers ("model") of the fire together with the unsteady heat-transfer models of the equipment (see chapter III.C), we may calculate the timing (*the first approach*) of functioning of the specific equipment during a fire (see Fig.8). In fact, for this scenario, all calculations and analysis can be performed preliminary, because the chosen "model" of fire development does not require current additional information about the actual fire.

2. Scenario 2.

This scenario assumes that we possess *the first group* of information, hence we know the exact location of the fire in a compartment. Even though it is impossible to apply a mathematical model of fire development, we may conduct specific calculations and approximately determine safety (in some extent) and potentially dangerous zones in a damaged compartment. Radzievski and Chnychkin (1987) showed that, in a closed compartment beneath of the level where the source of fire located, the gas temperature is almost unchanged during all period of fire development until its self-extinguishing. Based on this notion, they argued that all space of a compartment beneath the flame altitude is safety for the personnel and equipment with respect to the high temperature impact [Radzievski and Chnychkin, 1987].

The size and location of comparatively safety and dangerous zones might be determined by another way. According to equation (3.12), the ratio between both zones depends on the ratio between current and initial oxygen concentrations. On the other hand, it is known that the fire self-extinguishing occurs when the current oxygen concentration decreases to the critical meaning 0.12-0.13. If we assume that initial oxygen concentration equals regular atmospheric value, x_0=0.232, then, from equation (3.12), we can see that *maximum size potentially dangerous zone (a zone of thermal impact of the fire) is not more than 50% of entire volume of an damaged compartment.* The most interesting, that the size of this zone V_{Tmax} does not depend on the type of burning material, consequently, it might be preliminary estimated. Thus, we are able not only to recognize comparatively safety and dangerous zones in a damaged compartment (using [Radzievsky and Chnychkin, 1987]), but also to determine a maximum value of the dangerous zone.

As we see, the second scenario is more powerful than the first one though its abilities are also strongly restricted. It allows to determine approximately safety and dangerous zones in a damaged compartment, consequently we have a chance to correct our assessments with respect to the functioning of the equipment that were made on the basis of the first scenario. In addition, we may develop specific rules how to rescue the personnel that were not able to escape from the damaged compartment before its sealing.

3. Scenario 3.

This scenario assumes that we have information of the *first and second groups* (we know the place of the source of fire and specific types of the burning material and equipment). Such a combination of objective information permits to increase (though not very considerably with compare the second scenario) our assessing abilities. First, as in the second scenario, we are able to recognize and estimate the locations and sizes of the safety and dangerous zones within damaged compartment. Second, in some extent, we can estimate the timing self-extinguishing the fire development, τ_* (the first approach). Because we know what type of material or equipment is burning, we may also approximately estimate the firing surface (fire pool area), A_f. In order to do that, we may use equation (3.10) that should be transformed in a way for placing τ_* in the left side of the equation (3.10):

$$\tau_* = -\tau_0(1+\theta)/\theta \ln(x_* / x_0) \tag{3.16}$$

where x_* is the oxygen concentration in time of self-extinguishing (equals 0.12-0.13). This estimating the period of the fire is rather crude, but better then our assumption in the first scenario ($\tau_* = \infty$). Therefore, it is useful because it enhances our assessment the timing of functioning the equipment in a damaged compartment (second approach). Moreover, it allows to predict the largest possible duration of the fire from the beginning until its self-extinguishing.

4. Scenario 4.

The scenario assumes that we have information of the *fourth group*, hence we can observe the gas pressure in a damaged and nearby compartments. As we showed in the second chapter, monitoring the gas pressure and its rate in time considerably increase the opportunity to estimate and predict principal characteristics of the fire. In this case, we can examine and estimate such an important parameter as the scale of the fire, *Sc*, and predict the timing of self-extinguishing the fire, τ_* (second approach). Estimating the scale of the fire is crucial, because it permits to make a decision to suppress effectively the fire by choosing an appropriate extinguishing tool. In Reference [Nikitin, Rodin, 1991], an example of classification of the fire in terms of its scale and selection of appropriate methods and tools of the fire suppression was represented. According to [Nikitin, 198?], if the maximum rate of the gas pressure in a damaged compartment $\dot{p}_{\max} \leq 0.5/V$, then the fire pool area A_s is not more than 1.5-2.0m^2. So, the scale and hence the hazard of the fire is small. The appropriate decision might be:

- to inspect an accidental compartment by personnel for determining the fire location;
- to put out the fire by portable and semi-portable devices (extinguishers).

If $\dot{p}_{\max} \leq 2.0/V$, then the fire pool area is nearly 5m^2. Knowing the volume of the compartment, V, we can estimate the fire scale and hazard. Possible decision is

- To conduct quick inspection of the compartment for determining the fire location and to suppress the fire by appropriate fixed fire -extinguishing system.
- If the inspection is impossible or inefficient (the fire location is not recognized), to apply the most powerful means of the fire suppression that have extinguishing effect throughout entire compartment (for example, the halon extinguishing system).

Finally, if $\dot{p}_{\max} \geq 2.0/V$, then the fire scale is rather dangerous. Our decision must be fast and effective: without any preliminary inspection, to apply all possible means of fire suppression (fixed fire-extinguishing systems and even direct sinking the firing compartment by the seawater).

A similar procedure (or schema) as an efficient tool for decision making during fire fighting can be created for each ship or even for each compartment of ship where all peculiarities of a compartment and means of the fire suppression would be taken into account.

In addition to the scale of the fire, we have an opportunity to estimate more precisely than in scenario 3 the timing of the fire development (the second approach). As we showed above, in a sealed compartment, the maximum volume of atmosphere (the air) that is able to pass through the combustion zone is nearly 50% of entire volume a compartment V. On the other hand, it is known [see for example, Pomerantsev, (1986)] that the amount of thermal energy which can be released in an air volume unit, q_a during combustion process is approximately the same for each carbon material ($q_a \approx 3800 \text{kJ/m}^3$). Because the rate of the gas pressure $\dot{p}$ in a compartment is equivalent thermal energy released in each unit volume per unit of time, we can estimate the entire period of the fire by the next equation:

$$\tau_* = 0.5q_a / \dot{p}_{\max} \approx 0.5 \times 3{,}800 / \dot{p}_{\max} = 1{,}900 / \dot{p}_{\max} \qquad (3.17)$$

Monitoring the gas pressure and its rate allows to examine not only scale of the fire and predict the timing of self-extinguishing. It also permits to observe current particular phases of the fire development as well as success or failure of fire fighting actions conducted by personnel. For example, if the rate of the gas pressure rate increases, we can definitely conclude that the fire is spreading out and becoming more powerful and dangerous. If the gas pressure rate becomes steady (or quasi-steady), it means that the fire has already stabilized and not propagated anymore. Finally, if the gas pressure rate slows down, it definitely a signal that the fire has gone out. Monitoring the gas pressure also provides the opportunity to recognize objectively the moment of fire self-extinguishing by observing a specific gas pressure curve brake that is coincident with self-extinction of the fire [Nikitin, 1998a].

5. Scenario 5.

This scenario assumes that information of the first and third groups is available. In other words, we are able to recognize the location of the source of a fire within a compartment and to monitor the gas pressure. (But we can not indicate what types of materials or equipment are currently burning.) Obviously, it is possible to realize completely scenario 4. In addition, because of knowledge about a location of the source of a fire, we can recognize the volumes and location of the safety and potentially zones within a damaged compartment more accurately than in scenario 2 and 3. Unlike in the previous scenarios, we can determine not only extreme volumes of safety and dangerous zones at the final moment of the fire development, but we are able to estimate and observe the current meanings of these volumes in any unit of time. For example, we may calculate the current volume of the thermal impact zone V_T taking into account that this volume is consistent with a current volume of atmosphere of a compartment which currently has already passed through the combustion zone. Using specific combustion property of the air q_a and notion that a current total energy released by the fire equals the area under the gas pressure curve (see Fig. 10), a current thermal volume might be estimated by the next equation:

$$V_T = \frac{V\int_0^{\tau}(p - p_0)d\tau}{q_a} = \frac{V\int_0^{\tau}(p - p_0)d\tau}{3{,}800} \tag{3.18}$$

If a damaged compartment is divided by the decks and walls into several comparatively separated staterooms, cabins, etc., it is possible to indicate what exact rooms are currently dangerous or safety. It might be provided by the notion that the heat atmosphere of the fire will gradually propagate from the cabins located higher then the others to those that located lower or so. Thus, in any current moment, we will know not only the volume of the dangerous thermal zone, but also the cabins of a compartment where the gas temperature is dangerous for personnel and equipment. It is clear such an accurate estimation of the safety and dangerous zones within damaged compartment would allow alleviate some excessive restrictions with respect the timing of functioning the equipment that were conducted by the previous models (scenarios).

6. Scenario 6.

This scenario assumes availability of the first, second, and third groups of objective information about the fire. In addition to what we had known in scenario 5, we have possessed information of the types of currently burning materials. As a result, we are able additionally estimate and predict some new important parameters of the fire development:

- a fire pool area $A_{s.}$
- an average temperature schedule within a compartment during a fire.
- temperature variations with time for specific zones and cabins of a damaged compartment.

In essence, we are able to apply the models and methods that were described in paragraphs III.A-III.C of this chapter; therefore, from informative point of view, scenario 6 is the most powerful and accurate with respect CO capabilities to make command decision for suppressing the fire and ensuring the survivability of ship.

7. Scenarios 7, 8.

All these scenarios assume availability to gather and use information of the fourth group (with various combinations of information of the first three groups that were discussed before). Advantages and disadvantages of the smoke, gas temperature, and gas concentrations' monitoring we particularly discussed in Chapter I. This is powerful basis for applying DCIS, conducting the minute control on the fire development, and command decision making during a fire aboard. But this monitoring is quite expensive because it requires tremendous amounts of different types of sensors that have to be placed throughout all compartments of ship. It is possible and sometimes reasonable. But in some extent, the efficiency of this cumbersome informative system is barely higher than, for example, a system, which is based on monitoring a gas pressure in compartments, personnel inspections, and reports. The capabilities of such system, we have described by developing scenarios 1-6.

The entire picture that reflects alternative scenarios of the fire hazard analysis and applied models for estimating and predicting a fire development is briefly represented by the informative tree of the fire monitoring, hazard analysis, and command decisions (see Fig. 9). This tree of possible scenarios reflect a notion that capability to assess an emergent situation and to make an effective command decision heavily depends on opportunities to gather and apply original and current information about specific parameters of the fire and the gas atmosphere in a damaged compartment. When objective information is tiny or poor, the command decisions are uncertain and weak (scenario 1,2). And vice versa, than more accurate and appropriate objective information than more powerful, confident, and effective our analysis and command decisions, than more successful the ultimate results of the fire fighting procedures (scenarios 4,5 and higher).

E. CONCLUSION

First, based on the notion that during a fire aboard the opportunity of gathering objective information is rather restricted, an appropriate mathematical model and equations for estimating of fire development were described. The average temperature, oxygen concentration, and gas density within a damaged compartment can be calculated as functions of time during a fire development by means of corresponding analytical formulas.

Second, a model and analytical formulas for approximate estimating and predicting temperature in some specific zones (a thermal impact zone and a zone of comparative safety) of a compartment were received. The model is based on the notion that a volume of thermal zone within a damaged compartment, V_T, which is dangerous for personnel and equipment, constantly grows during a fire. The value of this volume is consistent with a current total volume of the compartment atmosphere, which has already passed through a combustion zone of the fire. The maximum meaning V_T equals nearly 50% of entire volume of a compartment, V, and in some extent it does not depend on type of burning materials and their combustion properties. This is an important statement because it permits to predict the dimensions of the dangerous and safe areas within a compartment during the fire, and their extreme values.

Third, the models for estimating and predicting the timing of functioning a ship's apparatuses and equipment should be designed. Because of thermal inertia, such models should be concerned on estimating unsteady heat-transfer processes between external temperature milieu of the fire and internal components of each specific apparatus that is crucial for functioning the entire technical system. In fact, the timing of normal functioning will depend on the moment when temperature of an examined component raises up to critical meaning.

Fourth, unpredictability of a fire development, on the one hand, and distinctive potential opportunities for taking objective initial and current information about its principal parameters, on the other, require specific and flexible methods of the fire estimating and predicting. Specifically, the fire peculiarities pre-determine multi-variety of the fire modeling and hence multi-variety of possible scenarios of the fire hazard analysis. Depending on availability and quality of initial and current information about the fire and atmospheric conditions, *an information tree of possible alternative scenarios* of the fire hazard analysis, its development, and command decisions were discussed. This discussion has confirmed than more accurate and appropriate original and current information about the fire than more powerful, confident, and effective command decisions, than more successful ultimate results of the fire fighting procedures. This discussion has also confirmed certain informative benefits of gas pressure monitoring for fire hazard analysis and command decisions' support.

IV. ACTUAL CHRONOLOGICAL DIAGRAM AND EFFICIENCY OF THE GAS PRESSURE MONITORING FOR COMMAND DECISIONS DURING A FIRE ABOARD

Previous discussion about possible models and options of fire monitoring has demonstrated benefits and flaws of different types of objective information about the fire for efficiency of command decisions and effectiveness of the fire-fighting actions. In the first approach, it was shown the advantages of the gas pressure monitoring for fire modeling together with information technology application and consequently for entire fire-hazard analysis and command decision support. In this chapter, the advantages or possible disadvantages of applying the gas pressure monitoring in board DCIS fore command decision support during a fire will be discussed. Specifically, in terms of cost-benefit analysis, we will discuss our fundamental decision about whether to apply gas pressure monitoring and relevant fire modeling in board DCIS for efficiency increase of command decisions during a fire. This cost-benefit analysis will be conducted based on the decision theory and chronological decision tree diagrams' design [Raiffa, 1970; Lapin, 1991; Keeney and Raiffa, 1993].

A. COMMAND DECISIONS DURING A FIRE ARE THE DECISIONS WITH MULTIPLE OBJECTIVES AND UNCERTAIN ENVIRONMENT

A procedure of command decision making during a fire is always complicated and not obvious. This procedure is a sequence of some elementary decisions, which are made gradually. Each subsequent decision depends on the current situation and success or failure of implementing the previous command decision. In addition, and this is crucially important, even if a commanding officer has enough information about a fire, it is not automatically means that a following decision would be trivial, because the entire decision making procedure is conducted under pressure of multiple objectives and priorities. For example, if a fire occurred and was detected, a commanding officer might not order to use all possible ways of the fire suppression, because such a decision would excessive, it might cause considerable damage of the equipment in a fire compartment (by extinguishing agent), additional costs, or even failure of the other duties or combat performances. So, each decision would be made after trade-off between alternatives and objectives that are very often contradict each other.

On the other hand, because of the fire unpredictability and other aspects of environmental uncertainty, each command decision and its realization (action) would produce a spectrum of possible responses with some levels of probability. Thus, the entire procedure of command decisions, following actions of personnel, and probabilistic responses (events) of the environment shape a *tree of possible actions and events* that might be described in terms of the decision theory concept.

B. SIMPLIFICATION OF THE FIRE-FIGHTING PROCEDURE, CHOICE OF OBJECTIVES, AND DESIGN OF A DECISION TREE DIAGRAM

The entire procedure of the fire-fighting actions and command decisions is so complex and multi-variant that it barely can be adequately described in terms of classical decision theory. Therefore, this procedure should be simplified with respect to external multiple objectives and real chronological tree as well.

There several alternative objectives that can be established by a commanding officer (CO) of a ship when a fire occurs and fire-fighting actions are conducted. Among them are:

- To suppress the fire and continue being underwater.
- To suppress the fire and save the crew.
- To rescue the crew and provide survivability of the ship.
- To save the ship and to rescue the crew.
- To accomplish a combat duty, to suppress the fire, and to save the crew and the ship.
- To minimize casualties of the crew and damage of the ship and its equipment, and so forth.

From this list of objectives, we can see that depending on the chosen strategic goal, the command decisions, priorities, and following actions of the crew might be different. For our analysis, we have established the next objective (goal). If the fire occurs, our priorities are to suppress the fire as soon as possible in order to minimize the losses among personnel and damage of the ship and its equipment. Such objectives and priorities are consistent with performance of common regular duties of a ship, that, in this case, do not interfere with some specific combat operation priorities. Thus, the command decisions of a CO and following actions will be recognized as a success if, after fire suppression, the damage of the ship and its equipment is minimal.

In order to design a chronological decision tree diagram, we need to describe possible alternatives that might take place as a result of command decisions and possible outcomes of these acts. Analysis of the real fire accidents shows that, for the fire with large and small scales, a sequence of the command decisions (acts) and outcomes (events) are different. Moreover, the probabilities of the similar outcomes might be very different too. Therefore, it is quite reasonable to design and discuss chronological decision tree diagrams of the fire-fighting procedure for large-scale and for small-scale original fires separately. Such a division of our problem onto two parts not only simplifies its formalization in terms of the decision theory, but also permits to discuss some peculiarities that would be lost if we tried to design only single chronological decision tree diagram.

First, let's discuss a design of chronological decision tree diagram in the case of the large-scale fire emerge. Possible decision tree diagram can be described as shown in Figure 11. The first crucial decision (act # 1) is whether to use a gas pressure monitoring in DCIS for a fire scale detection or not. If we choose to use monitoring, then there are two alternative outcomes of this decision:

- the fire scale was correctly recognized (favorable outcome) with probability P_1.
- the fire scale was not recognized or was recognized incorrectly (unfavorable outcome) with probability P_2.

Each of these outcomes (events) induces necessity of making new decision about what kind of fire suppression tool should be chosen (act # 2). Possible alternatives (events):

- the fire extinguishing tool was appropriately chosen, and the fire was suppressed with minimal costs and damages (final success). A probability of this event is P_3.
- the fire extinguishing tool was appropriately chosen, but the fire was not suppressed.

Because, originally, it was a large-scale fire, unfavorable actions of the fire suppression would produce the spread of the fire to nearby compartments and cause additional damage and costs. Probability of this event is P_4.

- the fire extinguishing tool was not correctly chosen (instead of fixed system because of large-scale fire, the fire extinguishers were chosen).

Nevertheless, the fire was suppressed. A probability of the event (though it is tiny) is P_5.

- --the fire-extinguishing tool was chosen incorrectly, as a result, the fire was not suppressed and began to spread. A probability of this event is P_6.

If the fixed extinguishing tool was appropriately chosen, but the suppression actions were unfavorable (event-fork node # 8, Fig.11), the fire might begin to spread and threaten nearby compartments. Therefore, the next command decision that should be made is to fill a damaged compartment with seawater in order to stop the fire (***act # 3***). This command decision and its performance might have two options:

- fire is suppressed and the ship is able to survive (final "success"). Probability is P_7 (and P_{13} for another branch of the tree diagram).

- filling a damaged compartment by the seawater is unsuccessful, because it worsens the entire situation aboard and causes new damage to the ship. Probability is P_8 (and P_{14}).

Unfavorable outcome of the last decision (event-fork node # 14), eventually derives the need to make one more decision (act # 4), a decision about abandoning the ship that, in its turn, might produce at least two outcomes (options):

- abandoning might be accomplished favorably with minimal casualties and damage (final "success"). Probability is P_{11} (and P_{15}).

- abandoning might be conducted unfavorably with casualties and even the ship's catastrophe (final "failure"). Probability is P_{12} (and P_{16}).

Unfavorable outcome as a result of the choice of the fire extinguishers (act-fork node # 5 and event-fork node # 10), will induce necessity to choose the fixed fire suppression system (node # 12) which eventually might produce favorable and unfavorable outcomes with probabilities P9 and P10 correspondingly. In essence, this branch of the tree-diagram (from the node # 12 and so) is an exact replica of the branch from the node # 5 and so. The difference between these two branches is only the values of the corresponding outcome probabilities and final expected payoffs, because the last branch would be realized under worst conditions as a result of loosing time.

Refusal from the use of the gas pressure monitoring deprives DCIS an opportunity to recognize the fire scale. In terms of the decision theory, it means that the corresponding tree branch of the diagram (act-fork node # 26 and so) is absolutely the same as the branch when the gas pressure monitoring produces a fault result (act-fork node # 4 and so). In some extent, it is reasonable to assume that not only the structures of the branches are equivalent, but also corresponding outcome probabilities are equal. So, it is not necessary to describe this branch of the tree in detail (in Fig.11, this branch was shown only particularly).

In the case of a small-scale fire, the chronological decision tree diagram can be represented as shown in Figure 12. There are several differences between these two diagrams (see Fig. 11 and Fig.12). First, if the small fire scale was favorably recognized, the next command decision (act-fork node # 5, Fig.12) is to suppress the fire by the fire extinguishers, and then, if these actions were not favorable, to apply the fixed fire suppression system. In the case of the large-scale fire (Fig.11), after favorable recognition of the fire scale, the command decision is to apply the fixed fire suppression systems. Second, if the small fire scale was incorrectly recognized, the next decision would be to apply the fixed fire suppression systems that with great probability will extinguish the small fire. But such action would be excessive and consequently inappropriate. It will cause additional costs and other disadvantages, because of unjustified damage of the equipment by the extinguishing agents. Third, though some sequences of acts and outcomes and entire tree diagram for the small fire scale are similar to the diagram for the big scale fire, the probabilities of outcomes are different. Finally, as it will be shown later, the final payoffs of the similar diagrams' branches will be also different.

C. DETERMINING THE PAYOFFS AND ASSIGNING THE EVENT PROBABILITIES

In determining payoffs, we assume that, during a fire fighting procedure, each command decision, following actions of the crew, and outcomes will cause appropriate costs that are consistent with volume of the damage and destruction of the ship produces by the fire or by applying extinguishing agents. Our rough estimations show that installation of the gas pressure monitoring system aboard together with DCIS will cost not more than 0.5% of the entire cost of the ship (submarine). Suppose also that the cost of the ship is $1 billion. Thus, the payoff of the decision to install the gas pressure monitoring is $5 million. Depending on the scale of the fire, its duration, appropriate or inappropriate fire scale recognition, favorable or unfavorable actions of the crew, respecting payoffs (in terms of cash flows) would be different. In the case of the large-scale fire, our rough estimations of the partial cash flows and determined payoffs are represented in Table 4.1 and Table 4.2 (columns # 4). In the case of the small-scale fire, corresponding partial cash flows and payoffs are represented in Table 2 and Table 3

Assigning the event probabilities P_1-P_{16} for each case was also conducted separately. Doing this, we followed the next general assumptions:

- appropriate and well-timed fire suppression action induces bigger probability of success than inappropriate one.

- the same action conducted sooner will cause bigger probability of the favorable event, and vice versa.
- fire-fighting actions against the large-scale fire produces events with less favorable probabilities than similar fire-fighting actions against small-scale fire.

The assigned numbers of the event probabilities are represented in Table 4 and Table 5 respectively.

D. DECISION ANALYSIS (STRUCTURAL ANALYSIS OF THE DECISION TREE DIAGRAM)

After determining payoffs and assigning the event probabilities, we may calculate full probabilities and net payoffs for each possible final outcomes of the decision tree diagrams. A full probability of each possible outcomes is a product of the conditional probabilities P_1-P_{16} that take place on corresponding prune of the tree-diagram. The values of the full probabilities for each outcome and their expected payoffs are represented in Fig.2-5 (columns # 3). Because the criterion of selecting the act with the maximum expected payoffs was the Bayes decision rule, we calculated and inserted in Table 2-5 (column # 5) the products of expected payoffs and full probabilities for each possible outcome respectively.

In Table 8, total expected payoffs different cases are represented. As we can see, in the case of the large-scale fire emerge, total payoffs are considerably less if we make decision to apply the gas pressure monitoring in DCIS. The advantages of use this monitoring for the small-scale fire are not so obvious though the total payoffs are also less. Thus, we can definitely conclude that the decision to apply gas pressure monitoring will be quite beneficial, especially in the case of the large-scale fire.

E. CONCLUSION

First, a procedure of command decision making during a fire is always complicated and not obvious, because it is conducted under pressure of multiple objectives and the unpredictable character of a fire. Therefore, such a procedure might be formalized in terms of the decision theory concept.

Second, based on this concept, the task of the cost evaluation of our decision to apply the gas pressure monitoring for support command decisions and fire-fighting actions was accomplished. Relevant decision tree diagrams were designed, and corresponding payoffs and conditional event probabilities were estimated.

Third, structural and cost-benefit analysis of the decision-tree diagrams shows that application of the gas pressure monitoring and relevant methods of recognizing a fire scale, will be definitely beneficial for efficiency increase of the entire process of the command decisions and the crew fire fighting actions as well. Conducted approximate assessments of the expected payoffs show that, in the case of applying the gas pressure monitoring, potential damages of the ship (with total cost $1 billion) from a single large-scale fire will be at least $38.5 million less than for the case of not applying a gas pressure monitoring. The cost of applying gas pressure monitoring was roughly estimated as $5million.

V. CONCLUSION

Our thesis examined opportunities for the application of information technology (IT) through development of a new method of fire-scale and fire expansion monitoring and mathematical modeling for the command decisions' support and providing the efficiency of fire-fighting procedure. Based on accomplished research and analysis, the next basic statements can be formulated:

First, despite of considerable progress with respect to IT implementation in board damage control informative systems (DCIS) for monitoring a fire and support of command decisions, some key-problems have not been solved. Among them are a reliable fire-scale recognition; an objective observation, predicting, and control over a fire development and success (or failure) of the fire-fighting actions. As a result, severe procedure of visual inspection of a damaged (firing) compartment by personnel, inappropriate command decisions about fire suppression, mistaken and inefficient crew actions have taken place.

Second, in the case of closed (sealed) compartment or entire ship (aircraft or space autonomous object) when internal atmosphere of the ship is separated from the earth atmosphere, the gas pressure monitoring is a very perspective way which can considerably enhance the effectiveness of the fire-fighting command decisions and suppression actions as well. Our research and analysis shows that the gas pressure monitoring and, particularly, monitoring the rate of the gas pressure variations during a fire, is very reliable and objective tool for estimating a fire scale, determining a fire ability to propagate through the ship, and detect a moment of the fire extinguishing.

These obvious advantages of the gas pressure monitoring for the command decisions and entire fire fighting procedure are combined with benefits of technical realization of measuring the gas pressure comparatively measuring other physical parameters of the compartment (ship) atmosphere: temperature or gases' concentrations. (The pressure field in a closed compartment is not so irregular as the others fields; therefore, the gas pressure measuring is much more technically simple and does not require to place considerable amounts of sensors.)

Third, it was shown that though mathematical modeling of the fire development is quite necessary, some objectives (such as the lack of initial specific information about original physical condition of atmosphere and actual parameters of the fire) do not permit to use the majority of the fire models in DCIS for fire hazard analysis and support of command decisions. Nevertheless, our research and analysis shows that it is possible to develop mathematical models that would be appropriate for DCIS. To demonstrate such an opportunity, some specific mathematical models were designed and discussed in chapter 3. These models were developed in a way of using only that initial and current information about atmospheric and fire parameters that are possible to observe during a fire aboard.

Fourth, "unpredictability" of a fire development, on the one hand, and distinctive potential opportunities for taking objective initial and current information about its principal parameters, on the other, require specific and flexible methods of the fire estimating and predicting. Specifically, the fire peculiarities pre-determine multi-variety of the fire modeling and hence multi-variety of possible scenarios of the fire-hazard analysis. Depending on availability and quality of initial and current information about the fire and atmospheric conditions, *an informative tree of possible alternative scenarios* of the fire hazard analysis, its development and command decisions were discussed. This discussion has confirmed than more accurate and appropriate original and current information about the fire than more powerful, confident, and effective command decisions, than more successful ultimate results of the fire fighting procedures. The discussion has also confirmed considerable informative perspectives of the gas pressure monitoring for fire -hazard analysis and command decisions' support.

Fifth, based on the decision theory, a cost-benefit analysis of the decision about whether to apply or not apply a gas pressure monitoring in DCIS for support of command decisions during a fire aboard was conducted. Relevant chronological decision tree diagrams were designed, and corresponding payoffs and conditional probabilities of the events were estimated. Formalization of so complicated and variable fire-fighting procedure in terms of the decision theory concept has permitted to conduct structural and cost benefit analysis of the command decisions during a fire and extract some interesting specific results. For example, it was shown that dramatic effect on the entire chronological decision-action procedure (tree diagram) and final success has the fire scale and appropriate choice a fire suppression tool. Structural and cost-benefit analysis also proved that application of the gas pressure monitoring in DCIS will not produce considerable additional costs. At the same time, it will permit to save considerable costs that usually caused by the fire itself and inappropriate and inefficient command decisions during a fire.

APPENDIX A. FIGURES

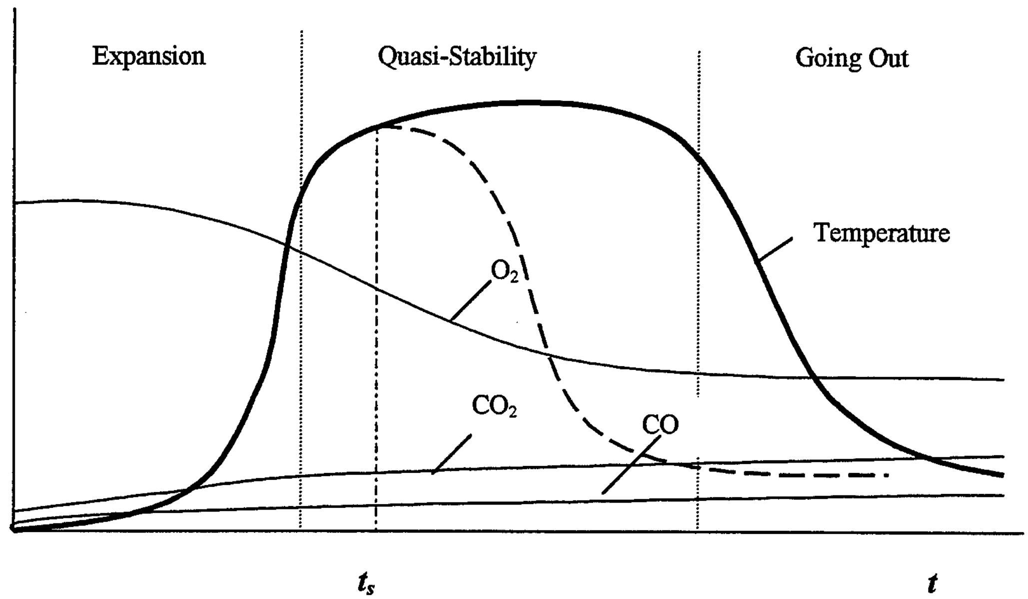

Figure 1: Variations of temperature, oxygen, CO, and CO_2 concentrations with time during a fire in a closed compartment

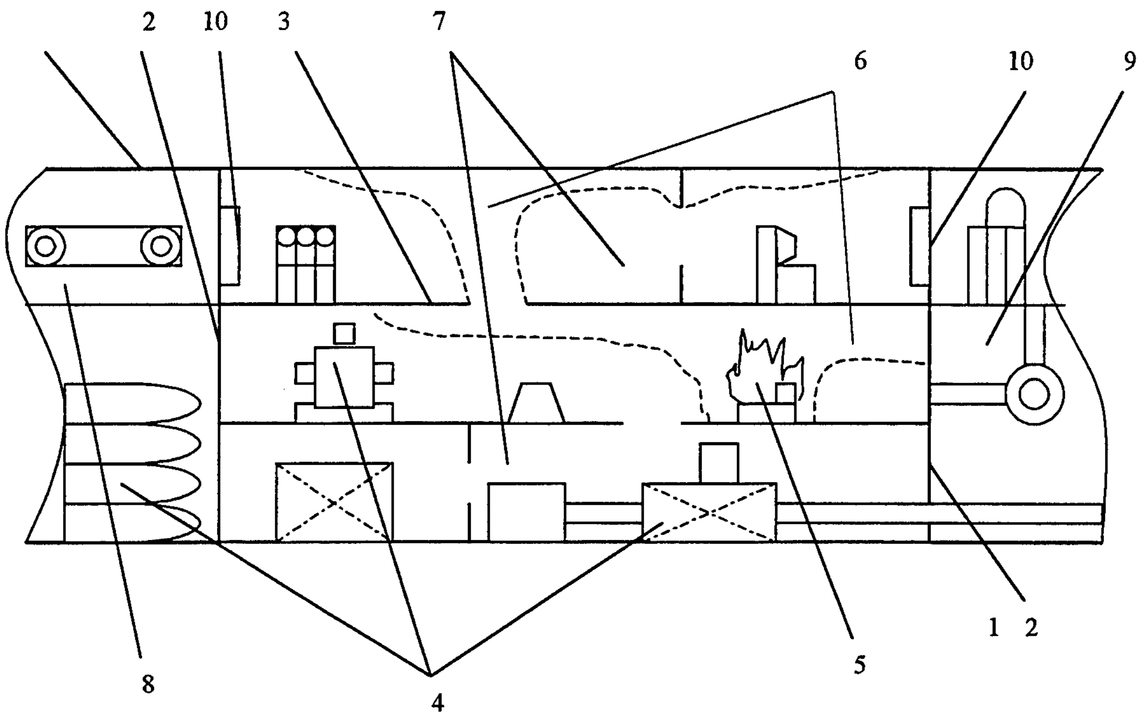

Figure 2. A fragment of a ship with a fire (accidental) compartment:

1--the hull of the ship (submarine).

2--water- and gas-tight sealed walls.

3--decks.

4--equipment.

5--source of fire.

6--thermal zone of the fire.

7--fire (damaged) compartment.

8,9--nearby (undamaged) compartments.

10--hatches.

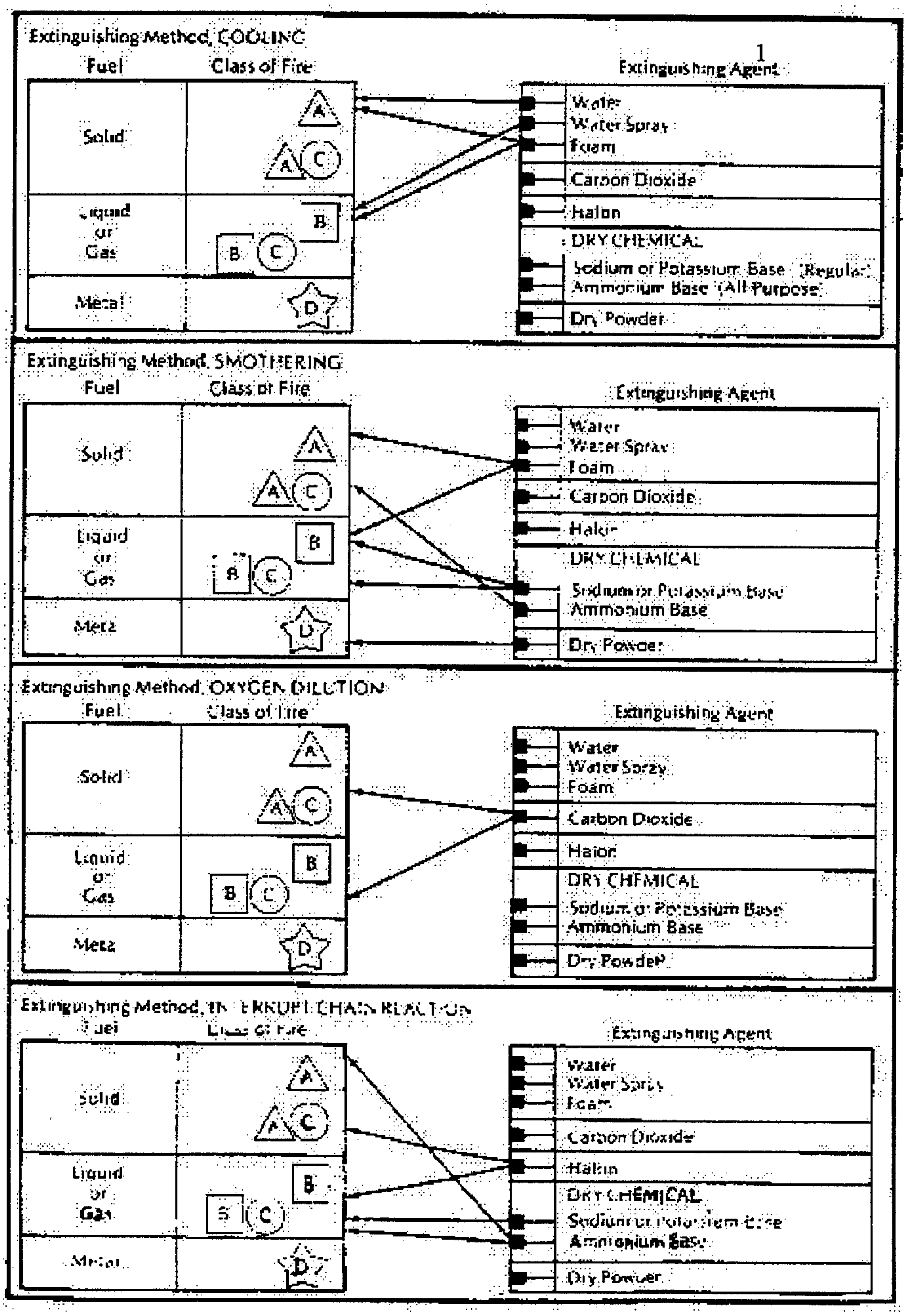

Figure 3. Acttions of Extinguishing Agents on the Different Classes of Fire

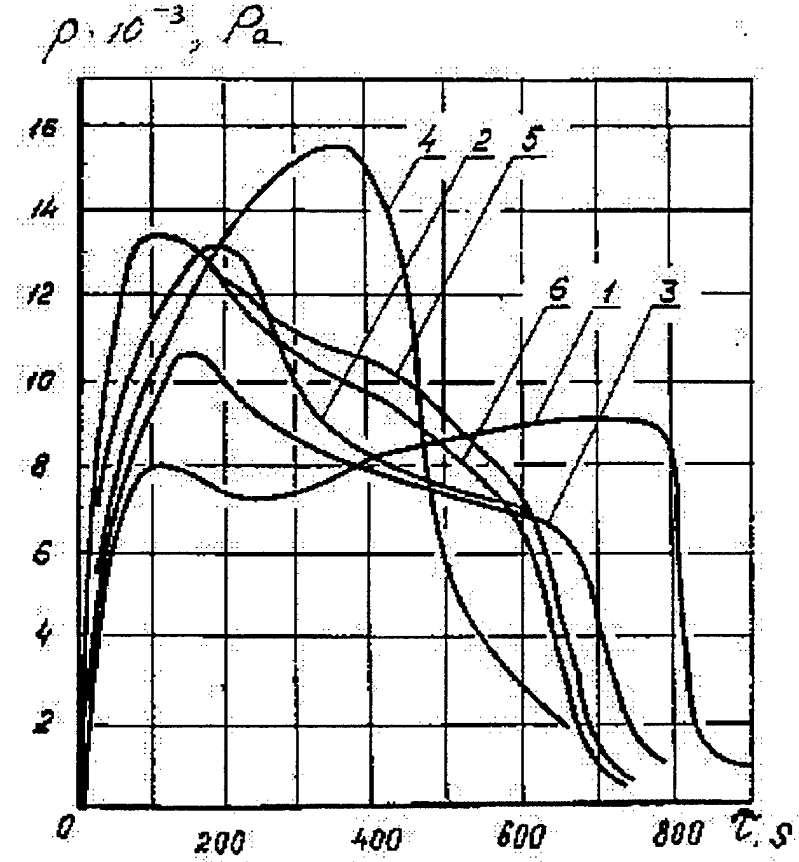

Figure 4. Variations of air pressure surplus (above initial value before the fire) with time during the fire in steal closed compartment (V=46m^3, burning material is diesel fuel placed on the fire pool, A_S=0.22m^2)

1--the fire pool at the center of the compartment (clearance between the fire pool and the ceiling, l=1.05m)
2--the fire pool by the flank wall, l=1.35m
3--the fire pool by the flank wall, l=1.35m, the equipment occupied the compartment space
4--the fire pool in the steel tube, l=2.9m
5--the fire pool by the front wall, l=1.35m
6--the fire pool by the front wall, l=1.35m,the compartment was occupied by the equipment.

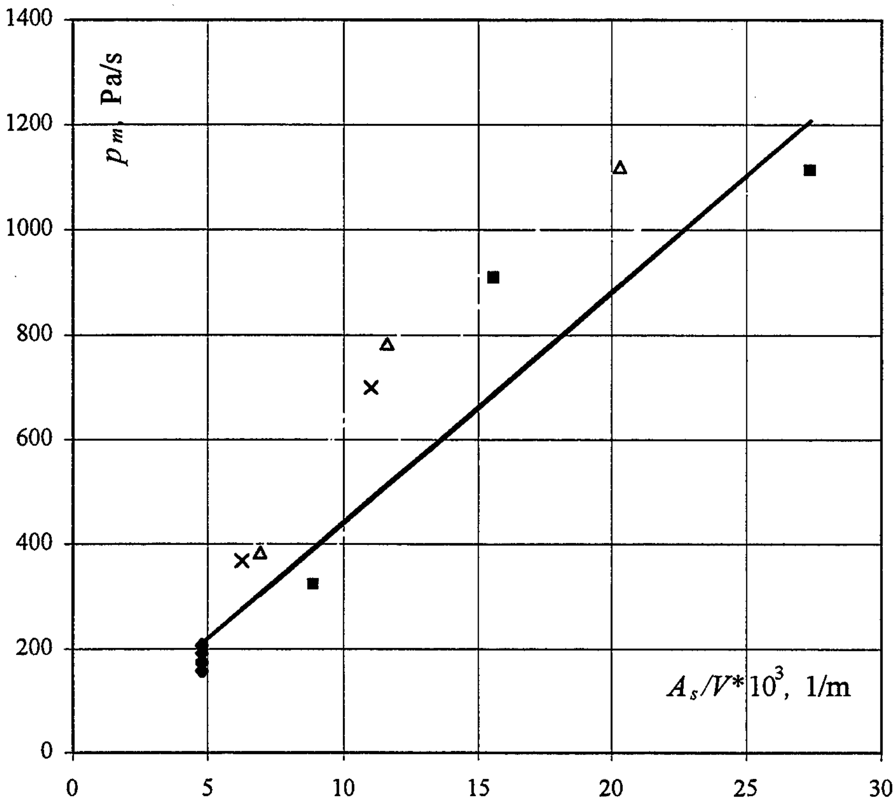

Figure 5. Variations of maximum rate of air pressure increase, $\dot{p}_m$, with ratio of fire area to volume of the compartment, A_s/V

Straight line--calculated via equations (2.15) and (2.16)
The dots--experimental data (V=13.5, 32, 46, and 164m^3)

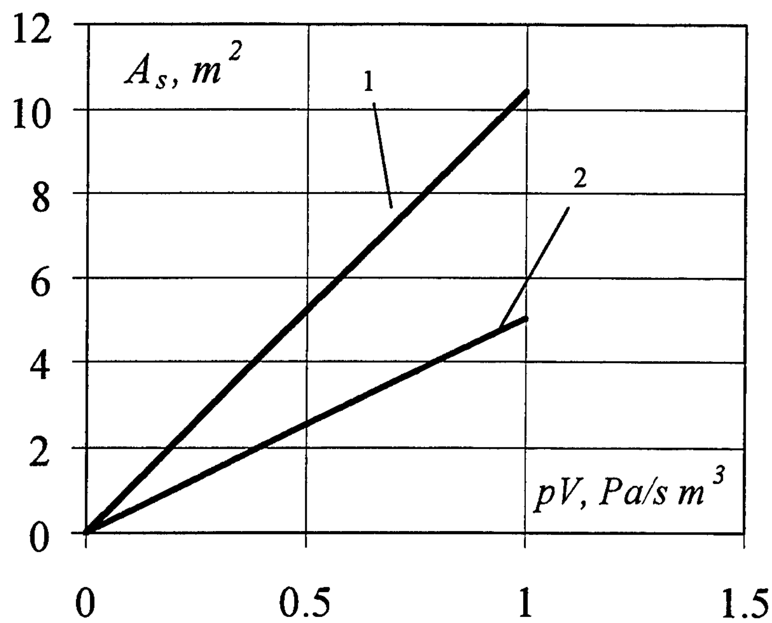

Figure 6. Variations of the fire pool area, A_S, with the range of meanings pV for two marginal burning materials

1-wood,
2--diesel fuel

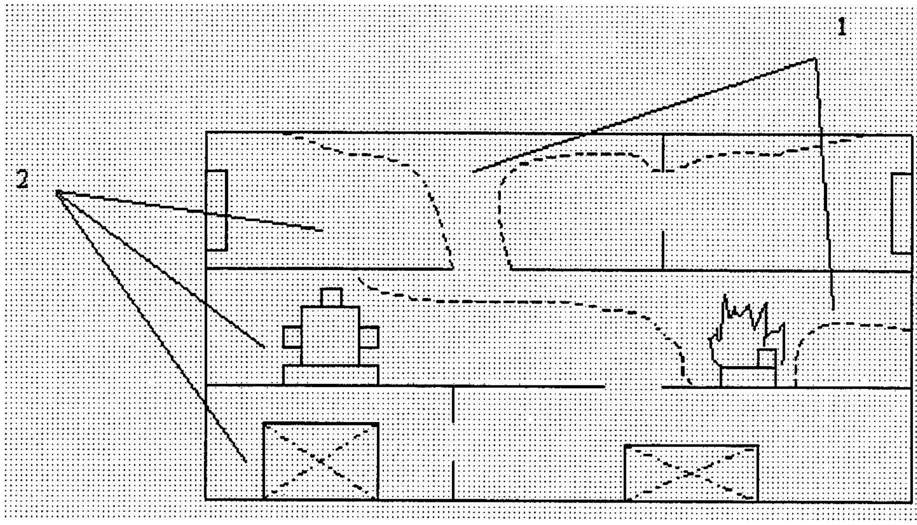

Figure 7. Temperature zones within fire compartment:

1--zone of thermal impact of the fire (dangerous zone)
2--zone of comparative safety

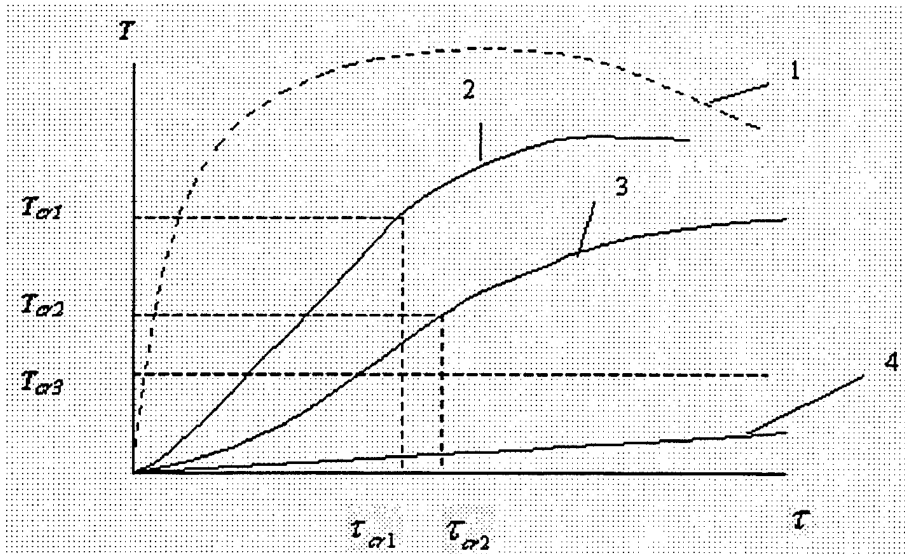

Figure 8. Estimating and predicting the timing of equipment functioning during a fire aboard:

1--temperature within a compartment

2--temperature regime of the most vulnerable element of the equipment unit # 1.

3--temperature regime of the most vulnerable element of the equipment unit # 2.

4--temperature regime of the most vulnerable element of the equipment unit # 3.

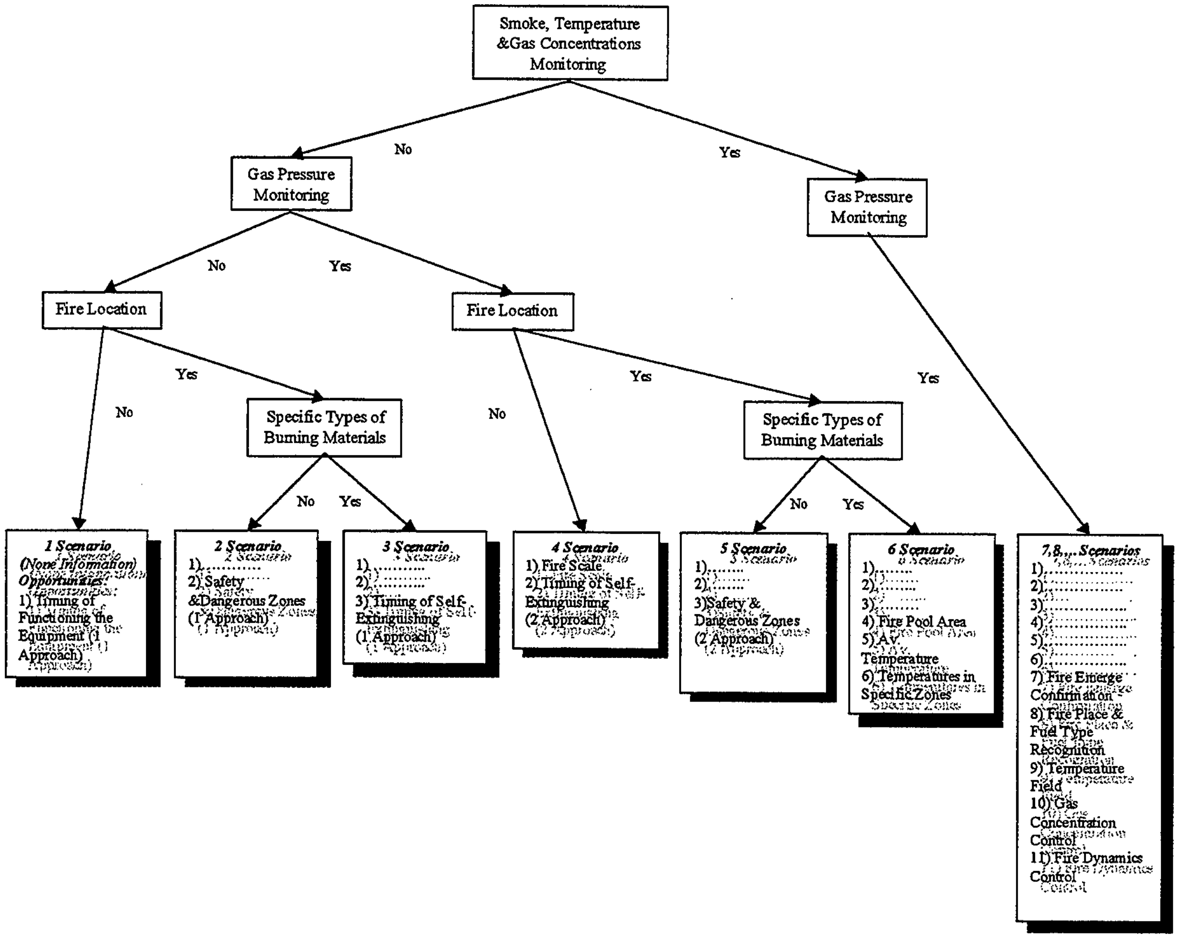

Figure 9. The of Possible Scenarios of Fire Hazard Analysis and Command Decisions

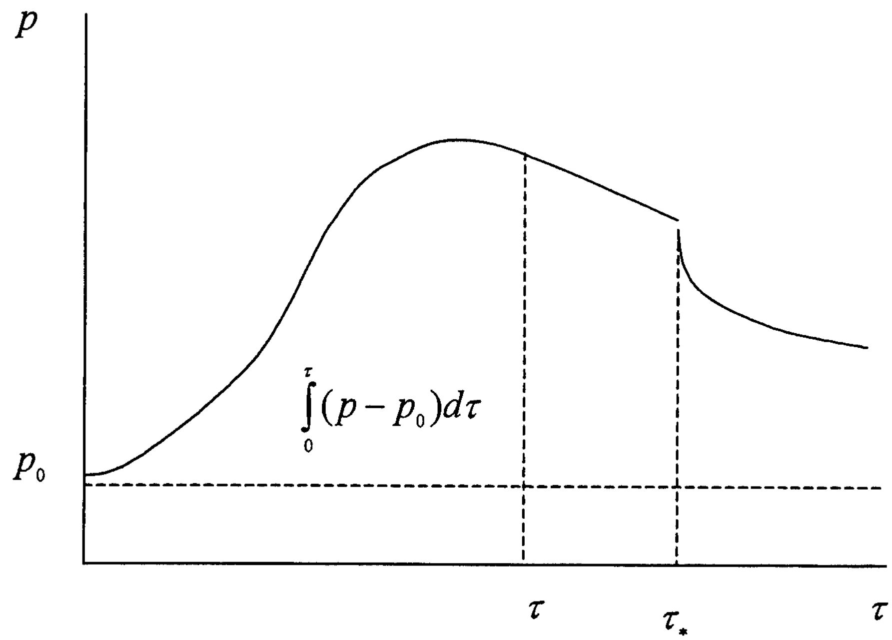

Figure 10. Variations of the gas pressure with time during a fire in a closed compartment

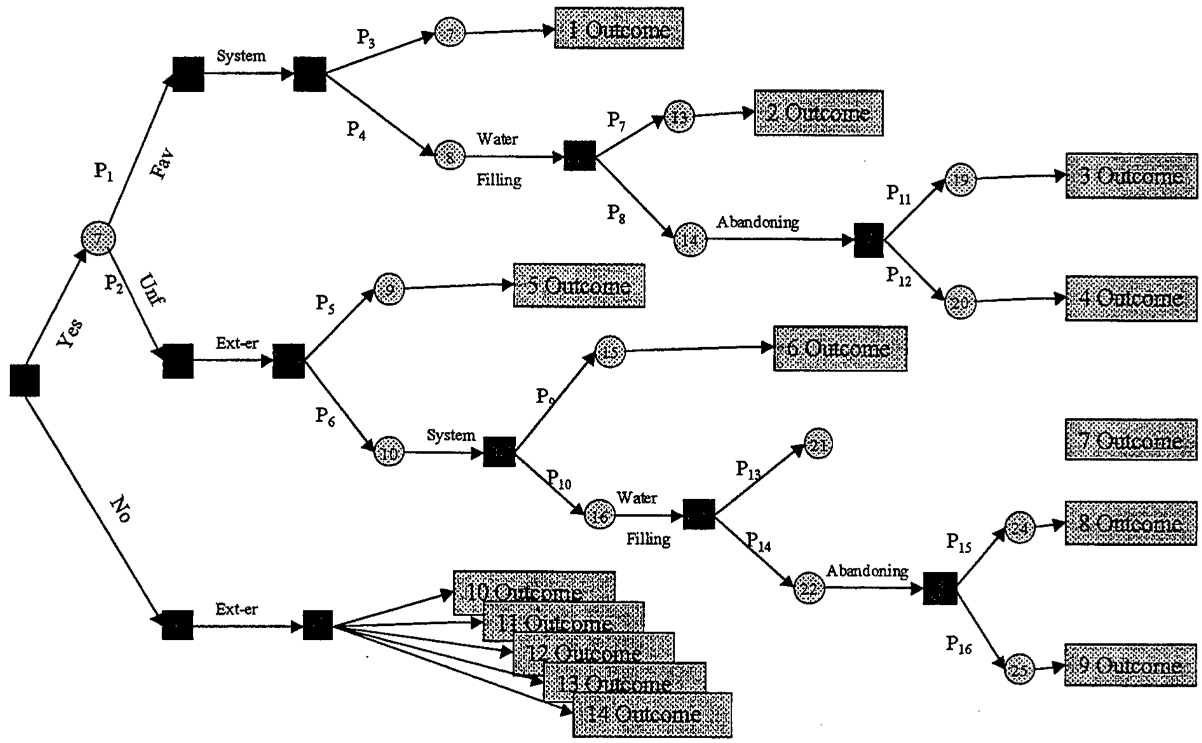

Figure 11. Chronological Decision Tree Diagram for the large-scale Fire

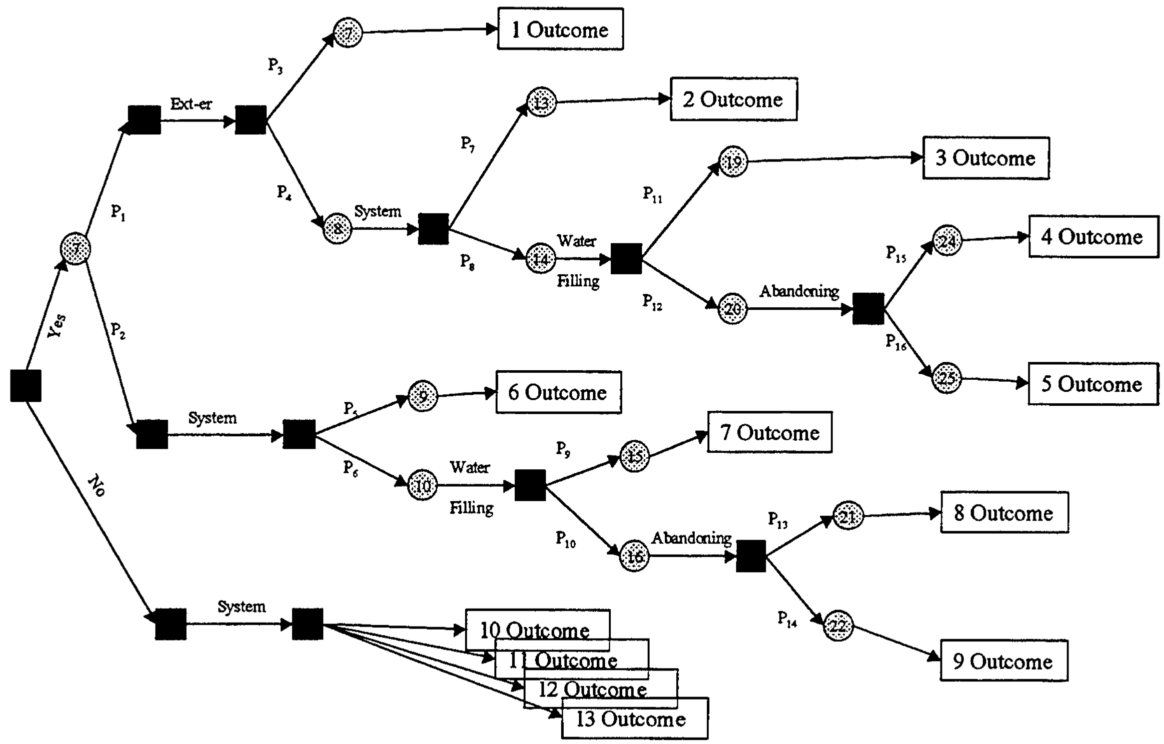

Figure 12. Chronological Decision Tree Diagram for Small-Scale Fire

APPENDIX B. TABLES

Table 1. Basic conditions and results of the full scale tests with the fires in the closed steel compartments (the burning material is diesel fuel

# of test seria	V, m^3	A_S, m^2	A_S/V, 1/m	$\dot{p}_m$, Pa/s
1	46	0.22	4.78	156
2	46	0.22	4.78	209
3	46	0.22	4.78	174
4	46	0.22	4.78	177
5	46	0.22	4.78	192
6	46	0.22	4.78	176
7	13.5	0.12	8.89	323
8	13.5	0.21	15.6	907
9	13.5	0.37	27.4	1112
10	32	0.22	6.88	383
11	32	0.37	11.6	785
12	32	0.65	20.3	1121
13	164	1.03	6.28	370
14	164	1.8	11	700

Table 2. Large-Scale Fire and Gas Pressure Monitoring

# of Outcome	Chronological Sequence of Command Decisions and Events	Probabil. of Outcome	Partial Cash Flows and Payoff (costs of damage), mln dollars	Payoff× Probab., mln dollars
1	2	3	4	5
1	Correct fire recognition, appropriate choice of the fixed system, favorable suppression act	0.72	\$50 --damage of the cmpt	-\$36
2	Correct fire recognition, appropriate choice of the fixed system, unfavorable suppression act, water filling the damaged compartment, favorable result	0.162	\$100--damage of the cmpt	-\$16.2
3	Correct fire recognition, appropriate choice of the fixed system, unfavorable suppression act, water filling the damaged compartment, unfavorable result, favorable abandoning of the ship (ship was not sunk),	0.0144	\$100--damage of the cpmt \$300--abandoning cost	-\$5.76
4	Correct fire recognition, appropriate choice of the fixed system, unfavorable suppression act, unfavorable water filling the damaged compartment, unfavorable abandoning of the ship (casualties and death of ship)	0.0036	\$1,000--cost of the ship death	-\$3.6
5	Incorrect fire recognition, inappropriate choice of the fire extinguishers, favorable suppression act	0.005	\$50 --damage of the cmpt	-\$ 0.25
6	Incorrect fire recognition, inappropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed extinguishing system, favorable suppression	0.0665	\$50 -- damage of the cmpt \$20--add. cost (loosing time)	-\$4.655
7	Incorrect fire recognition, inappropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed extinguishing system, unfavorable suppression, favorable water filling of the cmpt	0,0228	\$100--damage of water filled cmpt. \$20--add. cost (loosing time)	-\$2.736

8	Incorrect fire recognition, inappropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed extinguishing system, unfavorable suppression, unfavorable water filling of the compartment, unfavorable water filling of the compartment, favorable abandoning (ship was not sunk),	0.00399	\$100--damage of water filled cmpt. \$20--add. cost (loosing time) \$300--cost of abandoning	-\$1.676
9	Incorrect fire recognition, inappropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed extinguishing system, unfavorable suppression, unfavorable water filling of the compartment, unfavorable water filling of the compartment, unfavorable abandoning of the ship (casualties and death of the ship)	0.00171	\$1,000--cost of the ship death	-\$1.71
	Σ	1.000		-\$72.815

Table 3. Large-Scale Fire (None Gas Pressure Monitoring)

# of Out.	Chronological Sequence of Command Decisions and Events	Probab. of Outc.	Partial Cash Flows and Payoff (costs of damage), mln dollars	Payoff× Probab., mln dollars
1	2	3	4	5
10	Incorrect fire recognition, inappropriate choice of the fire extinguishers, favorable suppression act	0.05	$50 -- damage of the cmpt	-$ 2.5
11	Incorrect fire recognition, inappropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed extinguishing system, favorable suppression	0.665	$50 -- damage of the cmpt $20--add. cost (loosing time)	-$46.55
12	Incorrect fire recognition, inappropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed extinguishing system, unfavorable suppression, favorable water filling of the cmpt	0,228	$100-- damage of water filled cmpt. $20--add. cost (loosing time)	-$27.36
13	Incorrect fire recognition, inappropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed extinguishing system, unfavorable suppression, unfavorable water filling of the compartment, unfavorable water filling of the compartment, favorable abandoning (ship was not sunk),	0.0399	$100-- damage of water filled cmpt. $20--add. cost (loosing time) $300--cost of abandoning	-$16.76
14	Incorrect fire recognition, inappropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed extinguishing system, unfavorable suppression, unfavorable water filling of the compartment, unfavorable water filling of the compartment, unfavorable abandoning of the ship (casualties and death of the ship)	0.0171	$1,000--cost of the ship death	-$17.1
	Σ	1.00		$111.268

Table 4. Small-Scale Fire and Gas Pressure Monitoring

# of Out c	Chronological Sequence of Command Decisions and Events	Probab. of Outc.	Payoff (costs of damage), mln dollars	Payoff× Probability, mln. dollars
1	2	3	4	5
1	Correct fire recognition, appropriate choice of the fire extinguishers, favorable suppression act	0.72	\$1.0--damage of the cmpt	-\$72
2	Correct fire recognition, appropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed system, favorable suppression	0.064	\$50--damage of the cmpt	-\$3.2
3	Correct fire recognition, appropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed system, unfavorable suppression, favorable water filling of the cmpt.	0.0144		-\$1.44
4	Correct fire recognition, appropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed system, unfavorable suppression, unfavorable water filling of the cmpt, favorable abandoning of the ship.	.00144	\$100--damage of the cpmt \$300--cost of abandoning	-\$576
5	Correct fire recognition, appropriate choice of the fire extinguishers, unfavorable suppression act, choice of the fixed system, unfavorable suppression, unfavorable water filling of the cmpt, unfavorable abandoning of the ship (casualties and death of the ship).	.00016	\$1,000--cost of the ship death	-\$0.16
6	Incorrect fire recognition, excessive choice of the fixed fire systems, favorable fire suppression.	0.19	\$5--damage of the cmpt by excessive extinguishin g	-\$0.95

7	Incorrect fire recognition, excessive choice of the fixed fire systems, unfavorable fire suppression, water filling of the cmpt, favorable result	0,009	\$100--damage of water filled cmpt.	-\$0.9
8	Incorrect fire recognition, excessive choice of the fixed fire systems, unfavorable fire suppression, unfavorable water filling of the cmpt,	0.0009	\$100--damage of water filled cmpt. \$300--cost of abandoning	-\$0.36
9	Incorrect fire recognition, excessive choice of the fixed fire systems, unfavorable fire suppression, unfavorable water filling of the cmpt, unfavorable abandoning of the ship (casualties and death of the ship)	$1*10^{-6}$	\$1,000--cost of the ship death	-\$0.001
	Σ	1.000		-\$8.333

Table 5. Small-Scale Fire and None Gas Pressure Monitoring

# of Out c	Chronological Sequence of Command Decisions and Events	Probab of Outc.	Payoff (costs of damage), mln dollars	Payoff× Probability Mln dollars
1	2	3	4	5
10	Excessive choice of the fixed fire systems, favorable fire suppression.	0.35	\$5--damage of the cmpt by excessive extinguishing	-\$4.75
11	Excessive choice of the fixed fire systems, unfavorable fire suppression, water filling of the cmpt, favorable result	0,045	\$100--damage of water filled cmpt.	-\$4.5
12	Excessive choice of the fixed fire systems, unfavorable fire suppression, unfavorable water filling of the cmpt,	0.0045		-\$1.8
13	Excessive choice of the fixed fire systems, unfavorable fire suppression, unfavorable water filling of the cmpt, unfavorable abandoning of the ship (casualties and death of the ship)	$.5*10^{-6}$	\$1,000--cost of the ship death	-\$0.005
	Σ	1.000		-\$11.055

Table 6. The Event Probabilities for the Large-Scale Fire

Description of Event	Probability
Fire scale was correctly recognized, P_1	0.9
Fire scale was incorrectly recognized, P_2	0.1
After choosing the extinguishing system, the fire was favorably suppressed, P_3	0.8
After choosing the extinguishing system, the fire was not suppressed, P_4	0.2
After choosing the fire extinguisher, the large-scale fire was suppressed, P_5	0.05
After choosing the fire extinguisher, the large-scale fire was not suppressed, P_6	0.95
After unfavorable applying the extinguishing system and filling cmpt., the fire was suppressed, P_7	0.9
After unfavorable applying the extinguishing system and filling cmpt., the fire was not suppressed, P_8	0.1
Favorable abandoning (node # 19), P_{11}	0.8
Unfavorable abandoning (node # 20), P_{12}	0.2
Favorable fire suppression (node # 15), P_9	0.7
Unfavorable fire suppression (node # 16), P_{10}	0.3
Favorable fire suppression (node # 21), P_{13}	0.8
Unfavorable fire suppression (node # 22), P_{14}	0.2
Favorable abandoning (node # 24), P_{15}	0.7
Unfavorable abandoning (node # 25), P_{16}	0.3

Table 7. The Event Probabilities for the Small-Scale Fire

Description of Event	Probability
Fire scale was correctly recognized, P_1	0.8
Fire scale was incorrectly recognized, P_2	0.2
After choosing the fire extinguisher, the fire was favorably suppressed, P_3	0.9
After choosing the fire extinguisher, the fire was not suppressed, P_4	0.1
After choosing the fire extinguishing system, the small-scale fire was suppressed, P_5	0.95
After choosing the fire extinguishing system, the small-scale fire was not suppressed, P_6	0.05
Favorable fire suppression (node # 13), P_7	0.8
Unfavorable fire suppression (node # 14), P_8	0.2
Favorable fire suppression (node # 15), P_9	0.9
Unfavorable fire suppression (node # 16), P_{10}	0.1
Favorable fire suppression (node # 19), P_{11}	0.9
Unfavorable fire suppression (node # 20), P_{12}	0.1
Favorable abandoning (node # 21), P_{13}	0.9
Unfavorable abandoning (node # 22), P_{14}	0.1
Favorable abandoning (node # 24), P_{15}	0.9
Unfavorable abandoning (node # 25), P_{16}	0.1

Table 8. Total Expected Payoffs (without costs of the DCIS), ml dollars

	Large-Scale Fire	Small-Scale Fire
Applying the Gas Pressure Monitoring in DCIS	**-$72.815**	**-$8.028**
Not Applying the Gas Pressure Monitoring in DCIS	**-$111.268**	**-$10.052**

NOMENCLATURE

V--free volume of the compartment (the volume of air), m^3;

V_1, V_2, V_n --free volumes of the nearby compartments, (m^3);

V_T--volume of the thermal zone in a damaged compartment, (m^3);

k--ratio of specific heats c_p/c_v (--);

p--pressure of air (Pa);

$\dot{p}$ -- rate of air pressure variation with time, (Pa/s);

$\dot{p}_1, \dot{p}_2, \dot{p}_n$-- rates of air pressure variations with time in the nearby compartments, (Pa/s);

H-- low heat of the combustion of the fuel, (J/kg);

$\dot{m}$ -- mass combustion rate, (kg/s);

q_a-- energy released in one unit of the air during combustion reaction of a carbon fuel, (J/m^3);

Q_w-- total heat transferred per unit time from the flame and air to the constructions of compartment, (W);

Q_f-- radiative part of heat transferred per unit time from the flame to the constructions and wall of a compartment, (W);

$\dot{m}_s$ -- mass combustion rate per unit of the fire pool area, (kg/s m^2);

A_s--fire (or liquid) pool area, (m^2);

A_f= area of the flame surface, (m^2);

c_o=5.77 --radiation coefficient of a black body, (W $m^{-2}K^{-4}$);

T_f—mean external temperature of flame, (K);

T_w-- temperature of internal surface of the compartment, (K);

T_∞ -- temperature of air in a compartment, (K);

r--burning fuel mass rate, (--);

h_g-- enthalpy of the fuel vapor, (J/kg);

K-- combustion efficiency coefficient, (--);

$F_{f\text{-}w}$-- view factor between the flame surface and the constructions' surface of the compartment, (--);

l-- clearance between the fire pool and ceiling of a compartment, (m);

h_f-- height of the flame, (m);

C-- coefficient in equations 13 and 14, (s^3/kg);

$\dot{m}_{g1}$-- mass of the air (gases) flowing per unit time from an accidental compartment to the nearby compartment # 1, (kg/s);

$\dot{m}_{g2}$-- mass of the air (gases) flowing per unit time from an accidental compartment to the nearby compartment # 2, (kg/s);

R--universal gas constant, [J/(kg K)];

F--compartment internal surface area, (m^2).

Greek Symbols

τ -- time, (s);

τ_* -- fire duration from the beginning to self-extinction, (s);

η -- combustion efficiency, (--);

ε -- mutual emissivity, (--);

α --heat transfer coefficient between the fire and internal surface of a compartment, (W/m^2K);

ε_f -- emissivity of the flame, (--);

ε_w -- emissivity of the internal surface of the compartment, (--).

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